FAA Rotorcraft Damage Tolerance

FAA Rotorcraft Damage Tolerance (RCDT) and Health and Usage Monitoring Systems (HUMS) R&D Review Meeting

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OUTLINE

- Goal / Objectives
- Technical approaches
- Overall budget and expenditures status
- Technical issues/concerns
- Significant research results
- Summary of accomplishments
- Recommendations and planned research

Goal / Objectives

Goal Development Of Technology And Data For Adoption Of Rotorcraft Damage Tolerant Design, Certification, And Management

Objectives

RA 1 Identify and Document Rotorcraft Damage Tolerance Unique Issues

RA 3 Create Damage Database from Historical Data and Relate Data to EIFS.

RA 4 Collaborate With NASA/LARC, NASA/JSC and MSU in Developing Data and Testing Methods for Crack Growth Rate and Threshold

RA 5 Evaluate NDE Techniques for Small Crack Detection and Assess DT management Costs of Rotorcraft Components.

RA 6 Perform Coupons and Full Scale Component tests and Validate the Crack Growth Damage Tolerance Method

RA 8 Evaluate / Validate Fracture Mechanics and Crack Growth Codes and Perform Damage Tolerance Case Study for Rotorcraft Components.

RA 9 Characterize Randomness of Geometry, Material, Loading and Inspection Variables and Develop Probability Based Damage Tolerance Method

RA 10 Identify Primary Types of Rotorcraft Corrosion, Investigate Potential Corrosion Sensor Technologies, and Develop Corrosion Control Strategies

Technical Approaches

- Development of the FAA RCDT R&D Roadmap to identify technical needs in accordance with evolving FAA and DoD requirements.
- Coordinating with FAA, RITA members, NASA Research Centers, and Universities based on the "RCDT Roadmap"
- Leveraging technology and data from fixed wing aircraft and engines for the unique rotorcraft damage tolerance requirements

Sikorsky Tasks/RCDT Roadmap Areas

RA#	Task Title (Project Year)	00	01	02	03	04
1	RCDT specific issues study					
3	Damage Database & EIFS					
4	Crack growth rate database					
5	Non-Destructive Inspection					
6	Certification Testing					
7	Life enhancement methods			AACE Project		
8	Crack growth analysis					
9	Risk assessment					
10	Corrosion Control					

Note:
Blue Text indicates 2004 tasks

Technical Issues / Concerns

- DT methods have been advanced for use in isolated components / structures, however additional development is needed for more general applications
- High cycle fatigue crack growth and load interaction for rotorcraft loading spectra
- Characterization of product quality and damages (type, size, geometry) using EIFS concept
- Variation of material crack growth data especially near threshold
- NDE requirements, capabilities, and costs for small crack detection
- Reliable and efficient damage tolerance assessment tool
- Crack growth models for fretting fatigue
- Modeling fatigue growth in laser peening residual stress fields

Significant Results in 2004 Project

- RA 4 Crack Growth and Threshold Data

  Collaborating With MSU in Developing Data and Testing Methods for Crack Growth Rate and Threshold

- RA 6 Certification Testing

  Performed Coupons and Full Scale Component tests and Validate the Crack Growth Damage Tolerance Method

- RA 8 Crack Growth Analysis

  Evaluated / Validated Fracture Mechanics and Crack Growth Codes and Perform Damage Tolerance Case Study for Rotorcraft Components.

- RA 9 Risk Assessment

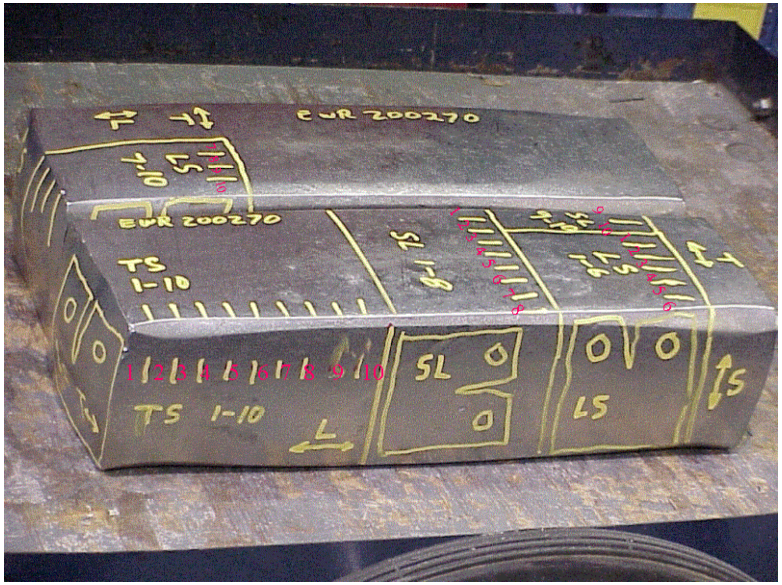
  Characterized Uncertainties of Geometry, Material, Loading and Inspection Variables and Develop Probability Based Damage Tolerance Method

RA 4: Crack Growth Data

- Coordinate with Bell and Boeing and interact with FAA, NASA and MSU
- Develop CG data and testing method
- Support FAA/MSU for Testing Method development
- Selected and purchased Ti-6Al-4V beta STOA
- Ti64 Beta STOA material conforming tests performed
- Location and orientation of specimens were planed, sketched and documented
- 30 specimen blanks in 3 orientations prepared and sent to MSU

Ti-6Al-4V Beta STOA Properties (Transv.)

Spec. ID	UTS (ksi)	Yield (ksi)	Elong	RA
T1A1	139	125	14	41
T2A1X	139	129	12	43

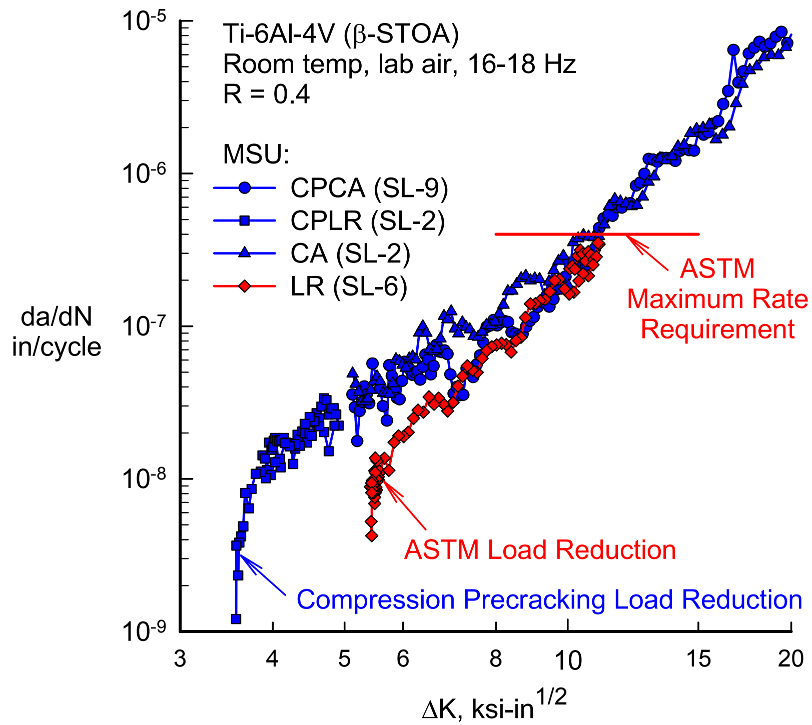


RA 4: Crack Growth Data

- Load-Reduction (LR) Procedure (ASTM Standard)
- Compression Pre-cracking Constant-Amplitude (CPCA) Testing Procedure
- Compression Pre-cracking Load-Reduction (CPLR) Testing Procedure
- Specimen machining completed at MSU
- 8 specimens completed by MSU using 3 testing methods

Updated Test Matrix (Dr. Newman)

Test Type	Material Orientation	R=0.1	R=0.4	R=0.7	R=0.8
CPCA or CPLR	LS	2	2	1	1
	SL	3	2	2	1
	ST/TS	2	2	1	1
LRI	LS	1	1	1	1
	SL	1	1	1	1
	ST/TS	1	1	1	1



Sample of Crack Growth Testing Data
(Dr. J.C. Newman, Jr.)

RA6: Certification Testing

Perform fatigue testing of coupons with flaws and stress concentration

- EIFS of notched and un-notched coupons studied
- Significant difference found in EIFSs for notched and un-notched coupons
- EIFS of flawed coupons without stress concentration studied
- The most critical flaw types determined
- Investigate effect of flaw on fatigue and EIFS of coupons with stress concentration

Perform fatigue testing of full scale dynamic components with flaws

- Leverage S-92 certification testing
- Validate of crack growth analysis
- Obtain EIFS of full scale components
- Obtain valuable crack growth / striation data

RA6: Certification Testing

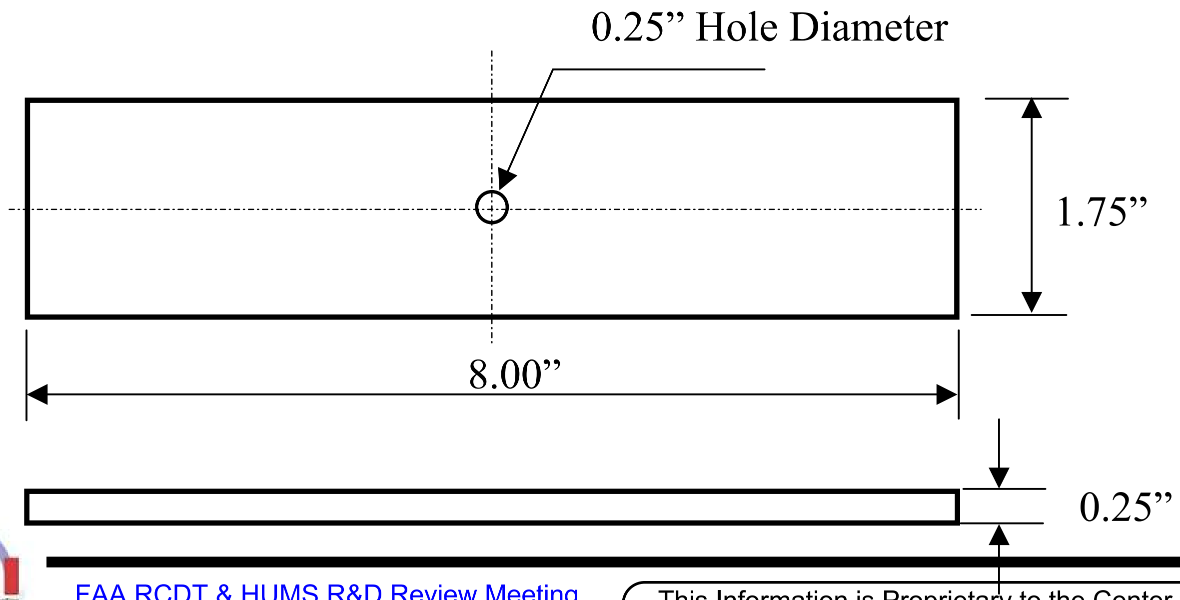
Material: Al7075-T7351 Orientation: L-T

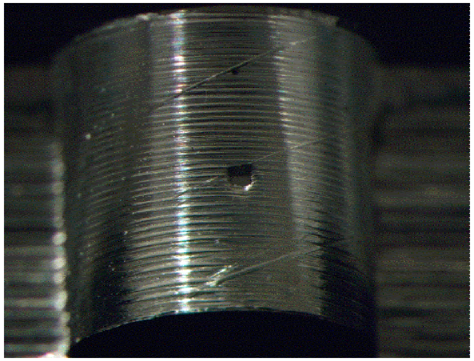
Specimen Type: Flat plate with flaws at hole

Testing Environment: Lab Air, Room Temperature

Flaw Types: As manufactured, 0.005” corrosion pit, 0.005” gouge

Flaw Type/Size (in.)	Number of Specimens	Stress 1	Stress 2	Spare
As machined/0	12	4	4	4
Corrosion/0.005	12	4	4	4
Gouge/0.005	12	4	4	4
Total	36	12	12	12



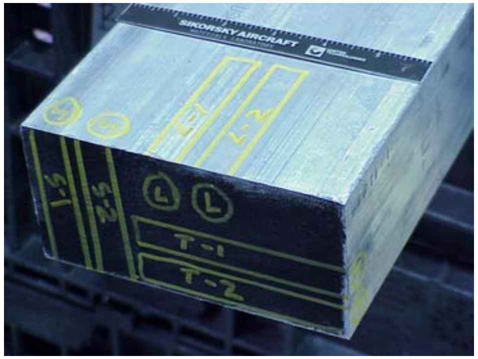


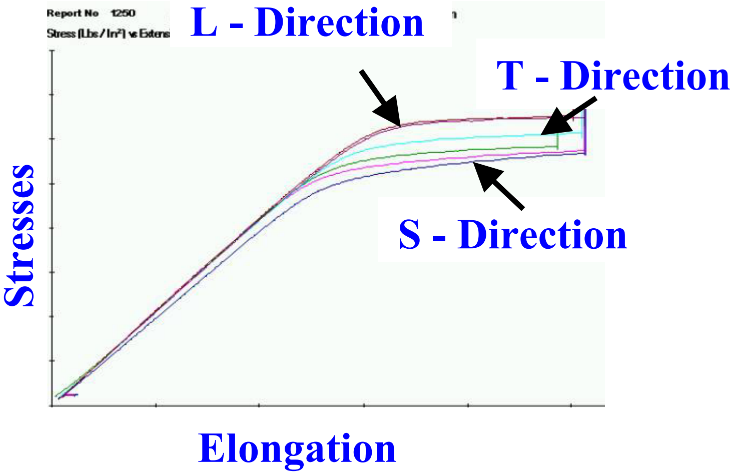
0.005” Deep Gouge

RA6: Certification Testing

Flawed Coupon Testing

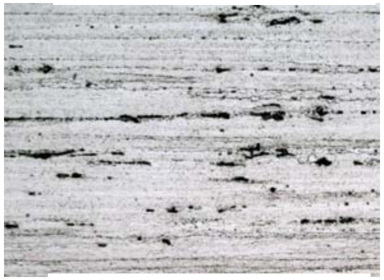
- Material Conformation Testing performed for 3 orientations
- Procedures for generating gouge and corrosion pit developed
- Strain survey performed
- Microstructures of the material studies





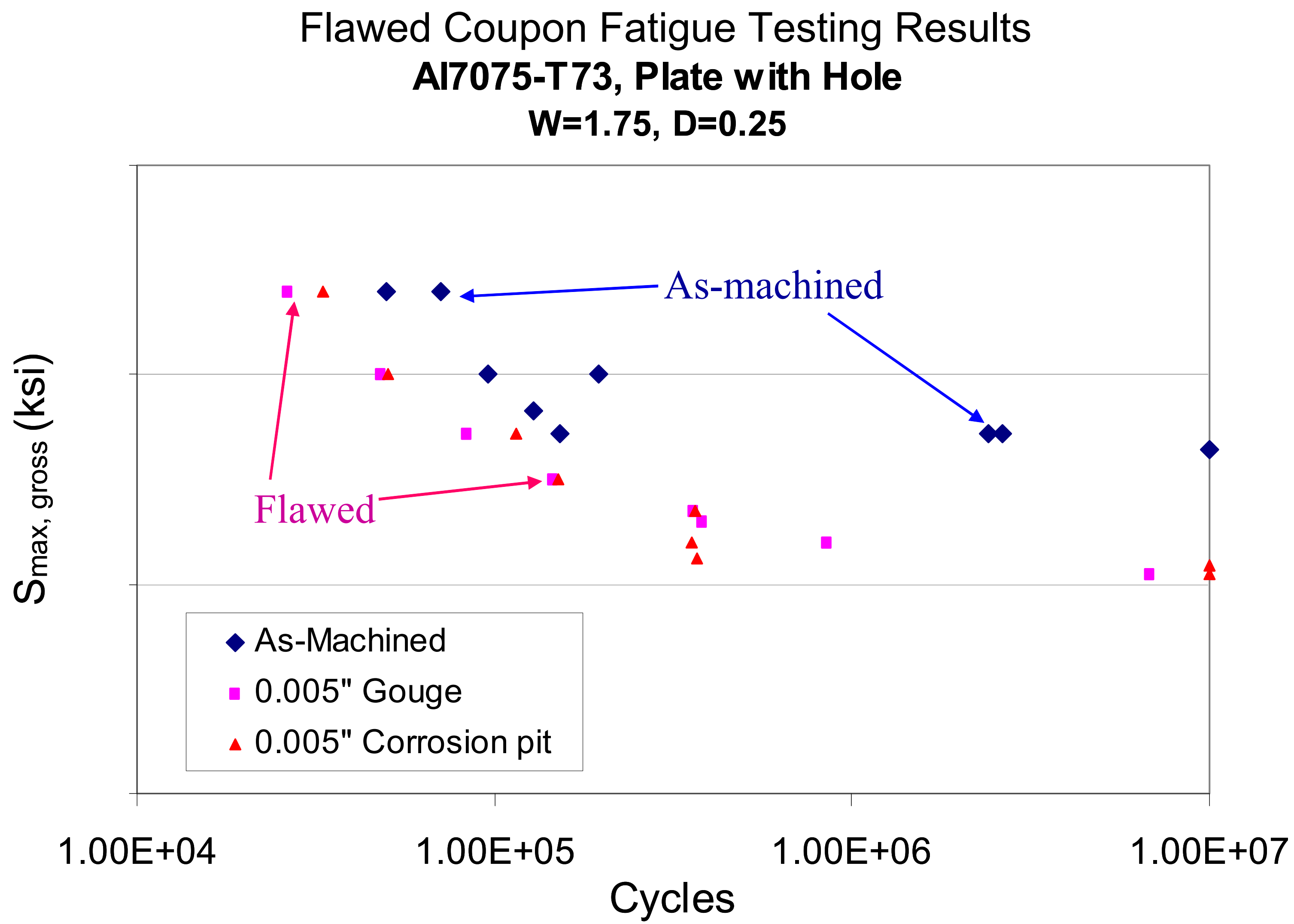
L - Direction

S - Direction

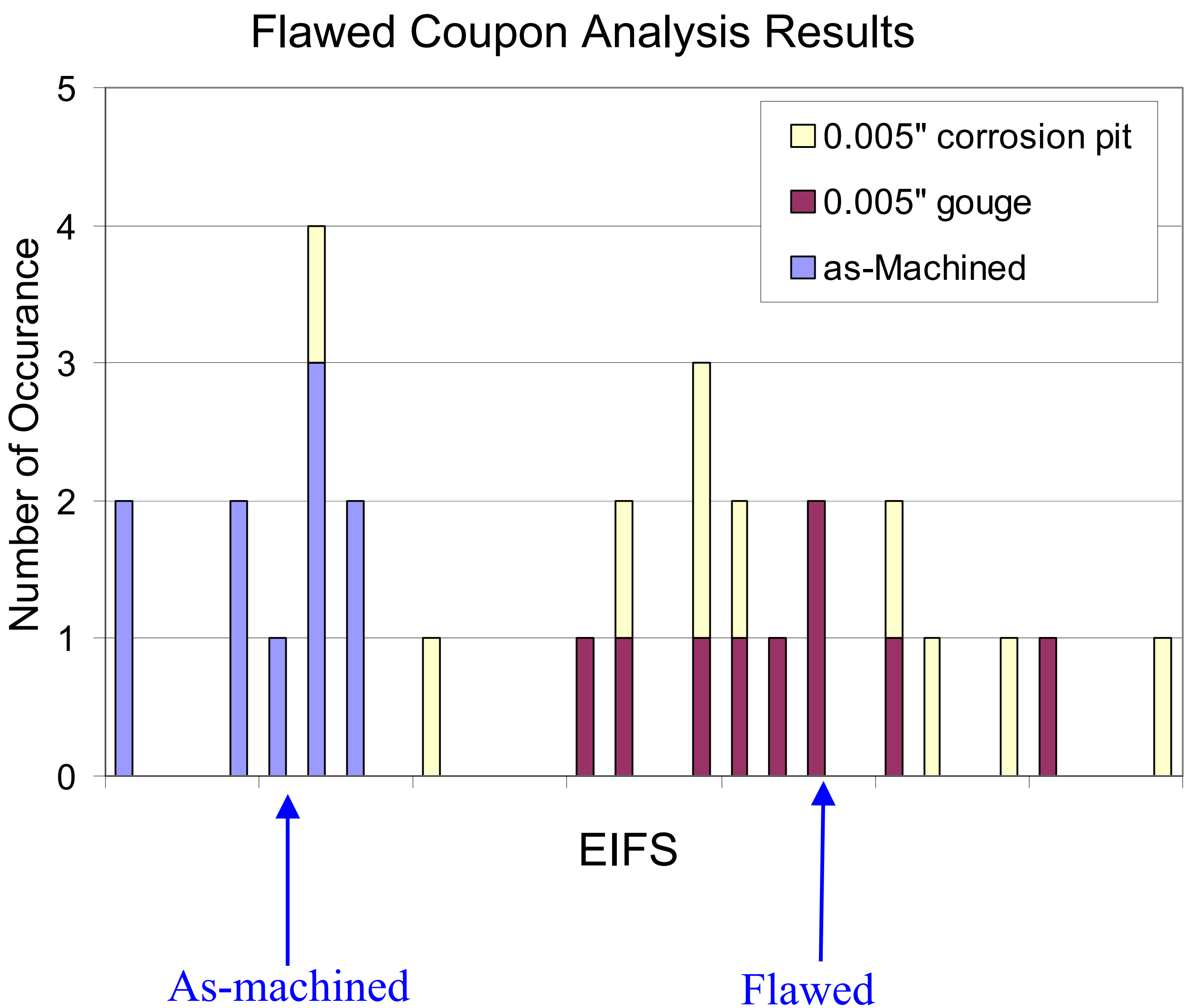


T - Direction

RA6: Certification Testing

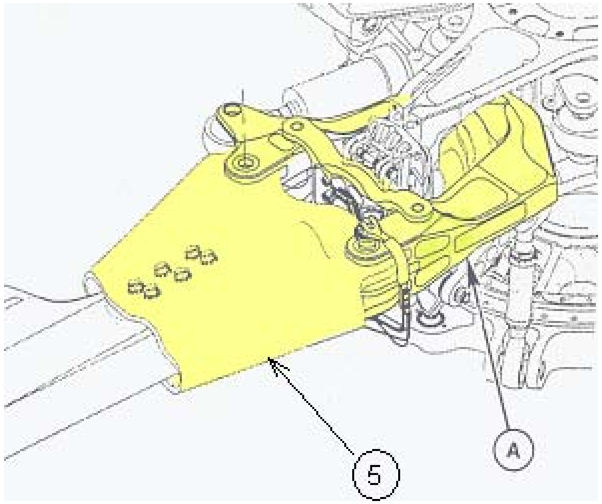


RA6: Certification Testing

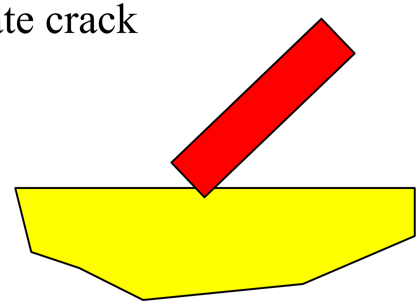


RA6: Certification Testing

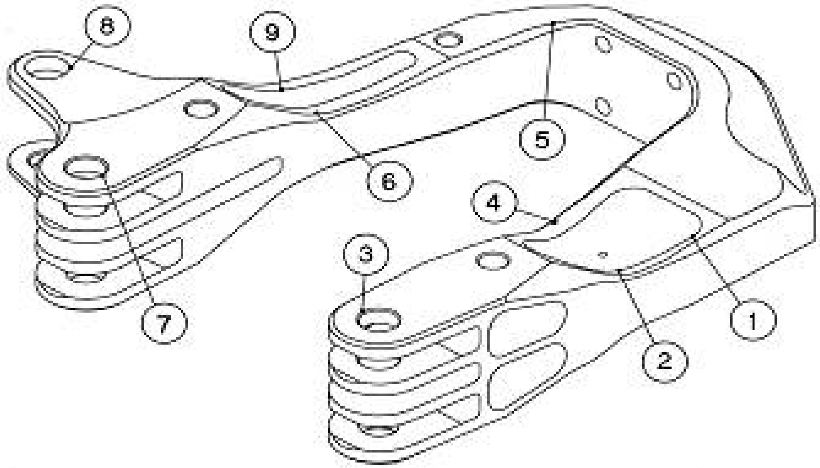
Full scale component testing
- Leverage certification testing, 2 M/R yoke tested
- Validate of crack growth analysis
- Obtain EIFS of component with flaws
- Obtain valuable crack growth / striation data



- Component: Main rotor yoke
- Material: Ti64 Beta STOA
- Flaws: 0.005” gouges artificially generated before test
- Previous crack: No crack data generated before this year
- Test load: Accelerated load level used to generate crack

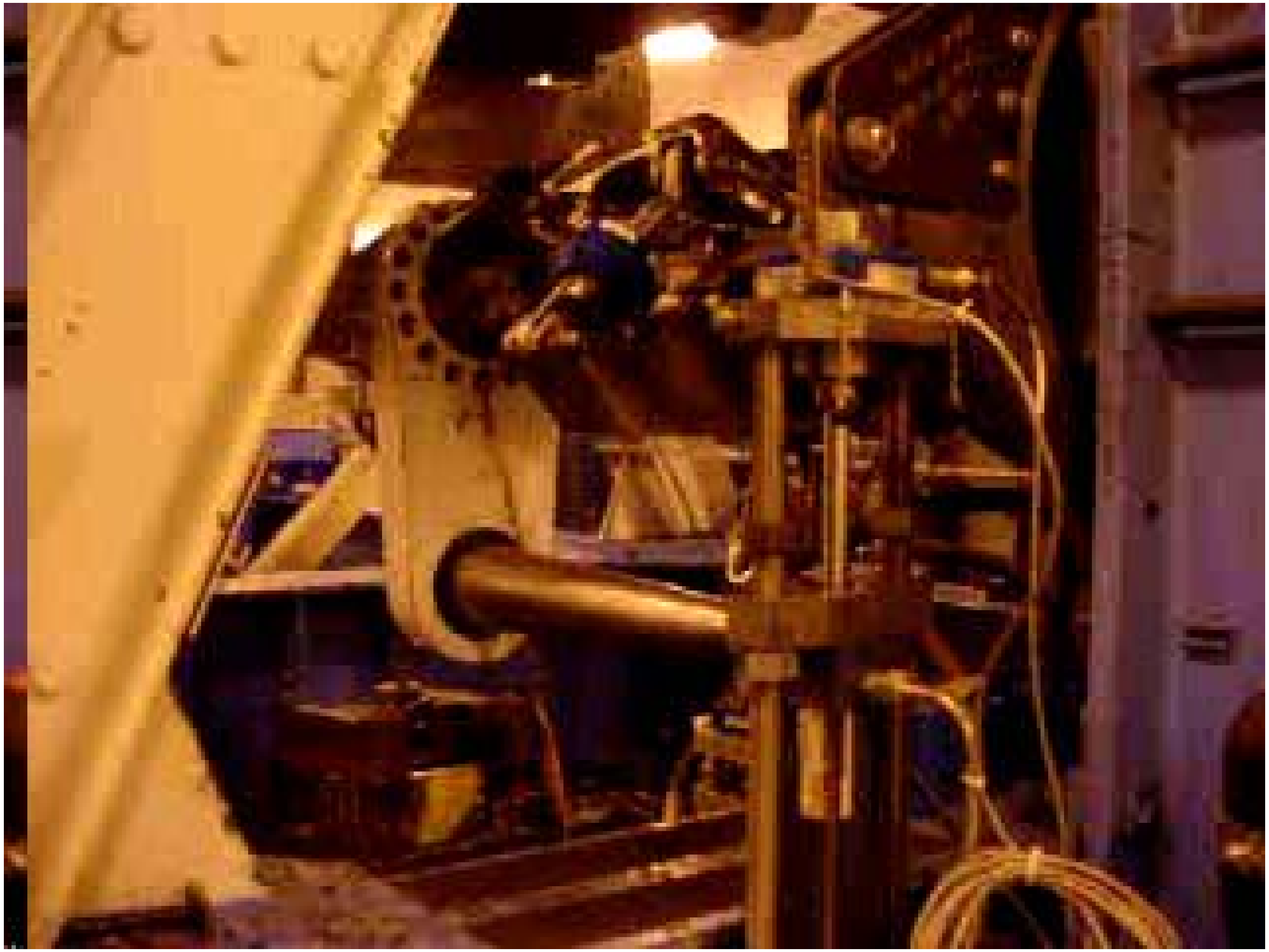


Method to generate gouges



RA6: Certification Testing

Main Rotor Yoke Test Setup

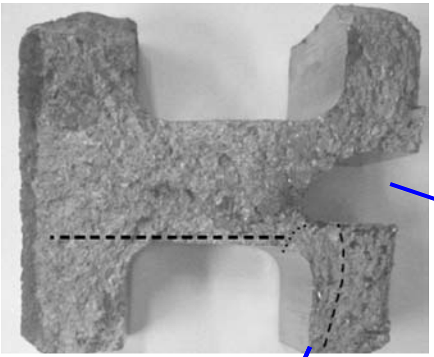


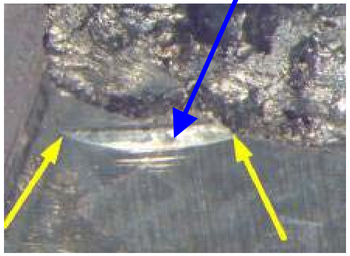
RA6: Certification Testing

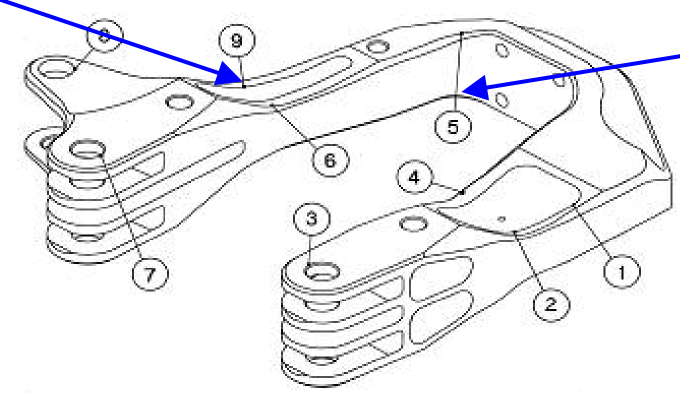
Mode 1

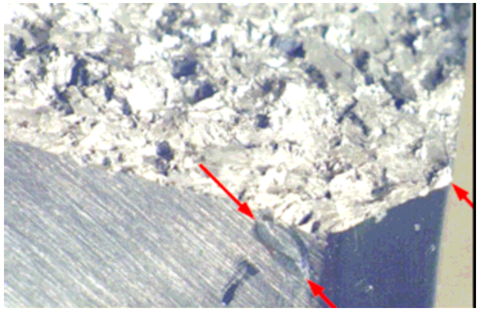
Mode 2

- Two fracture modes Generated
- Crack originated at flaws
- Striation counted for mode 1





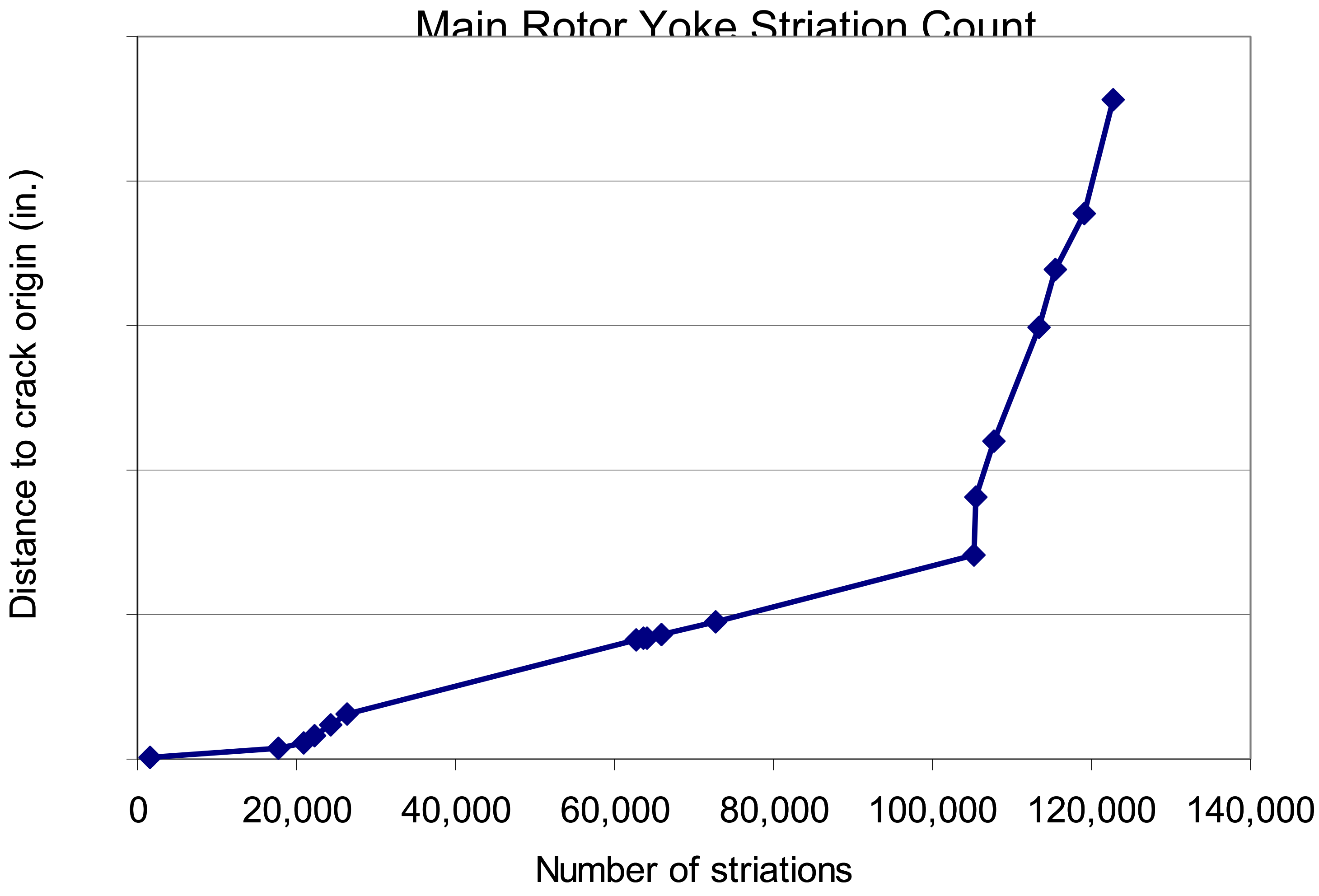




As shown the fatigue crack originated at a flaw

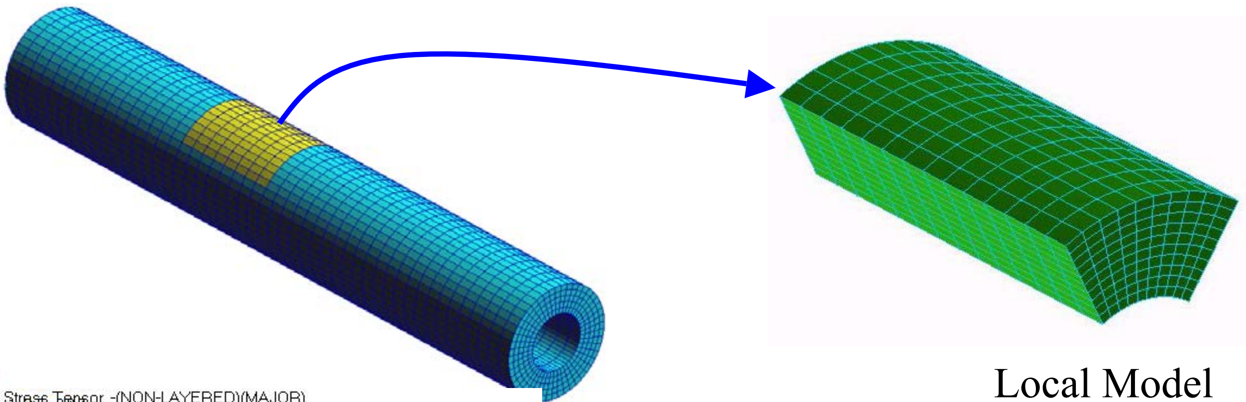
Close-up look view of the flaw

RA6: Certification Testing

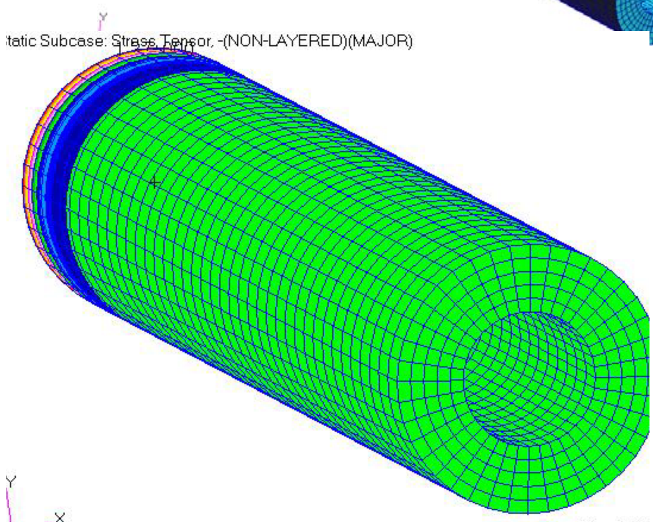


RA8: Crack Growth Analysis

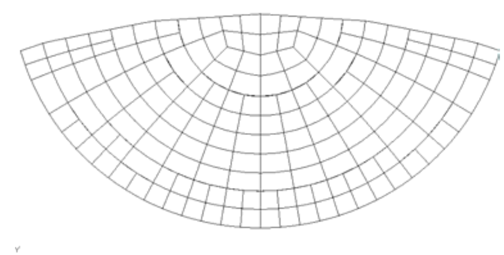
FM Code Evaluation: AGILE Workshop Problem 4 - Tension



Local Model



Global Model

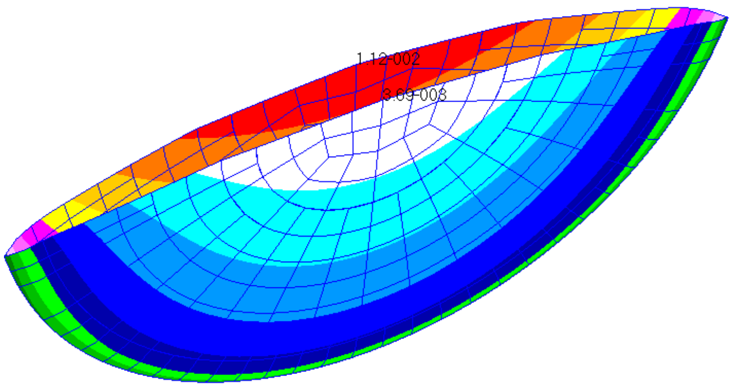


Crack Profile

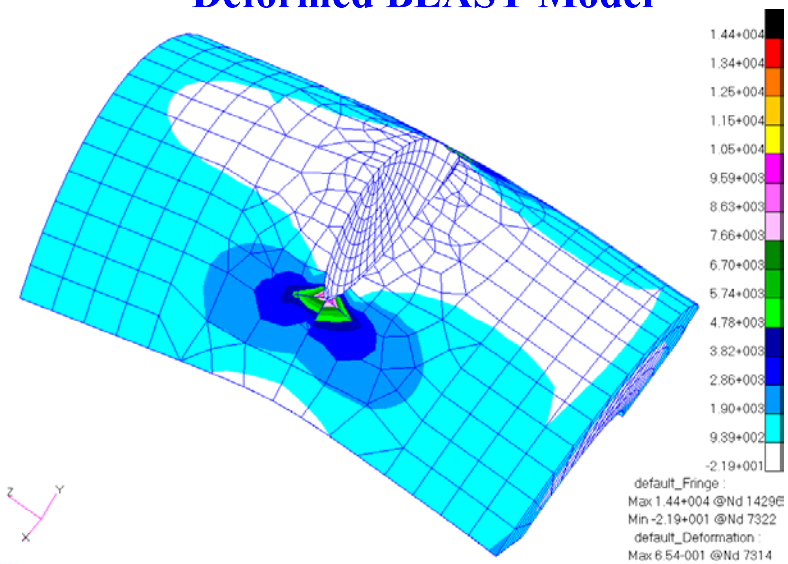
GOVERNMENT INDUSTRY ACADEMIA NRTC

RA8: Crack Growth Analysis

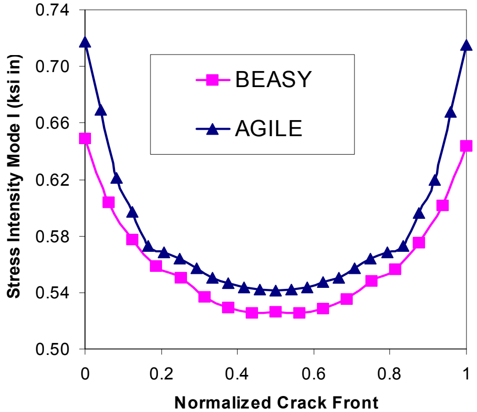
Opened BEASY Crack

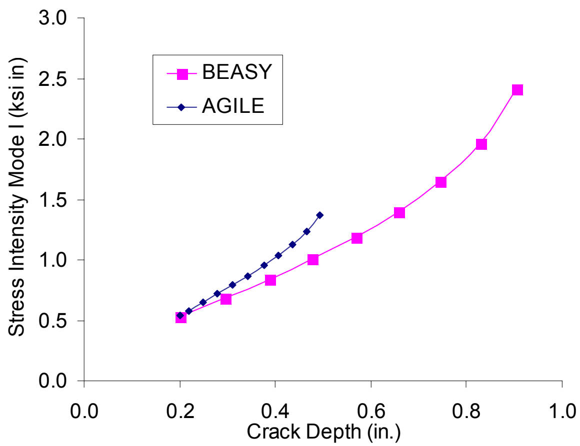


Deformed BEASY Model



Comparison of Stress Intensity From AGILE and BEASY

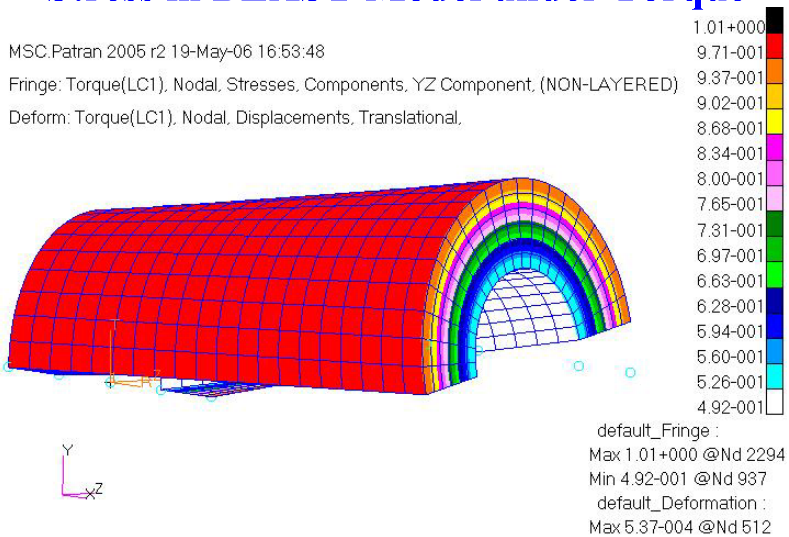




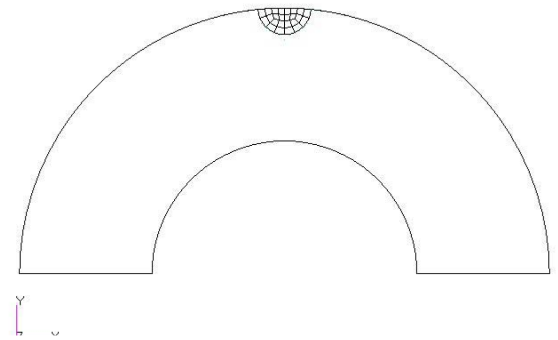
RA8: Crack Growth Analysis

FM Code Evaluation: AGILE Workshop Problem 4 - Torsion

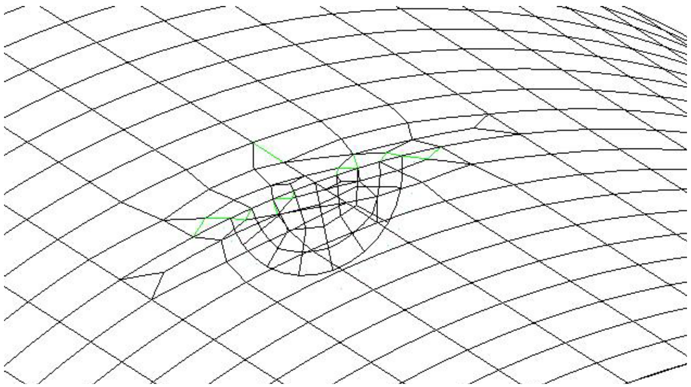
Stress in BEASY Model under Torque



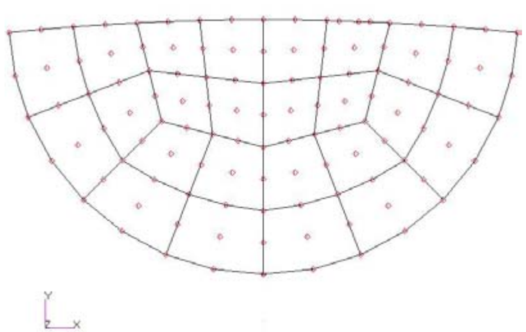
BEASY Model with Crack



BE Mesh Near Crack



Initial Crack



RA8: Crack Growth Analysis

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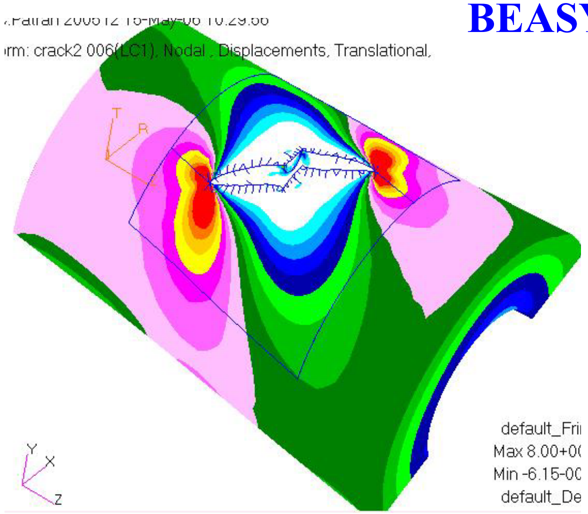
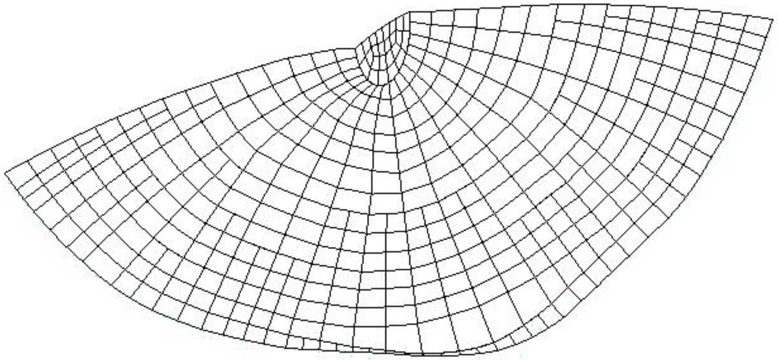
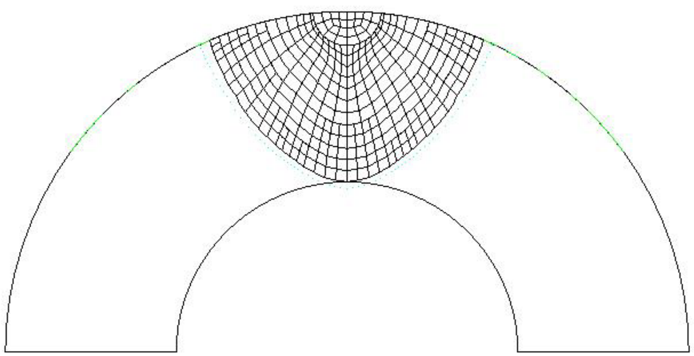
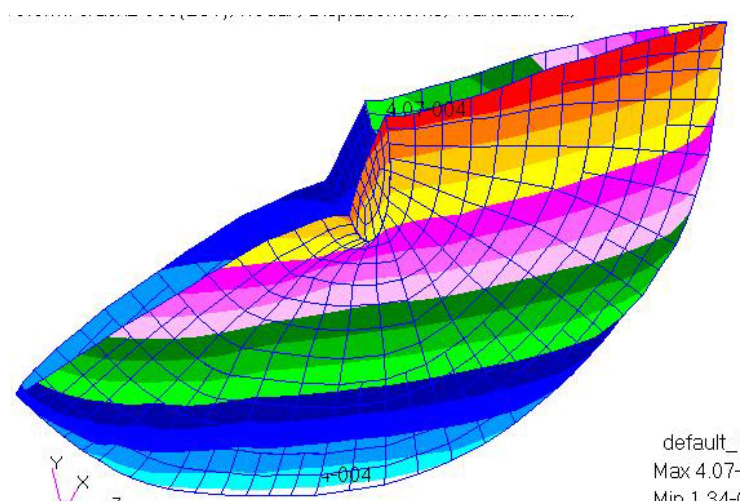
BEASY Predicted Crack Profiles







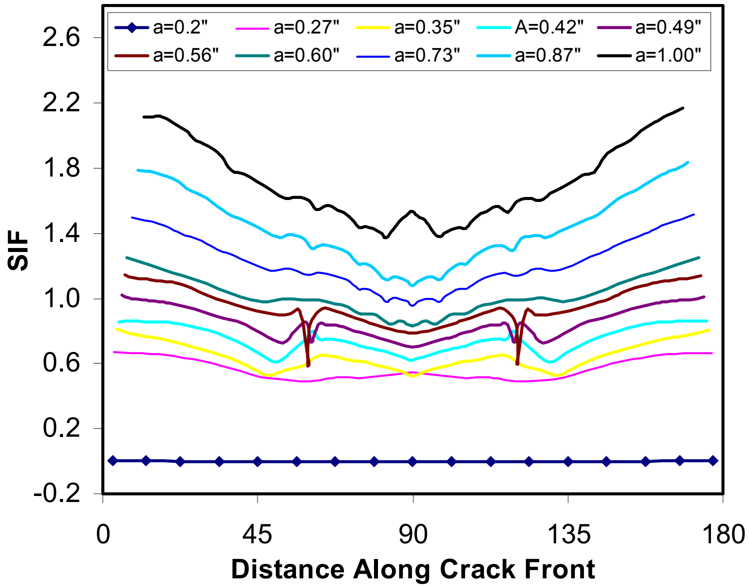


RA8: Crack Growth Analysis

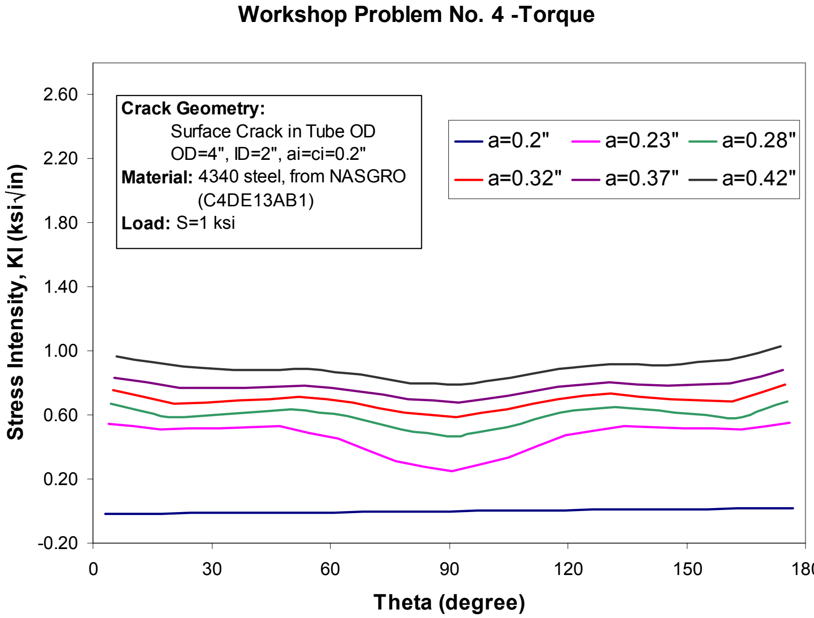
FM Code Evaluation: AGILE Workshop Problem 4 - Torsion

Comparison of BEASY and AGILE SI Solutions

BEASY Mode I



AGILE Mode I

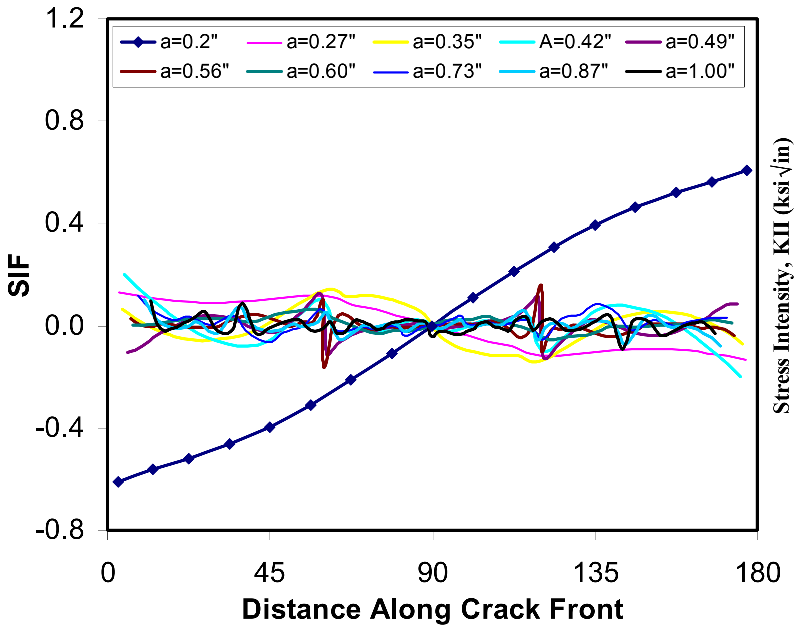


RA8: Crack Growth Analysis

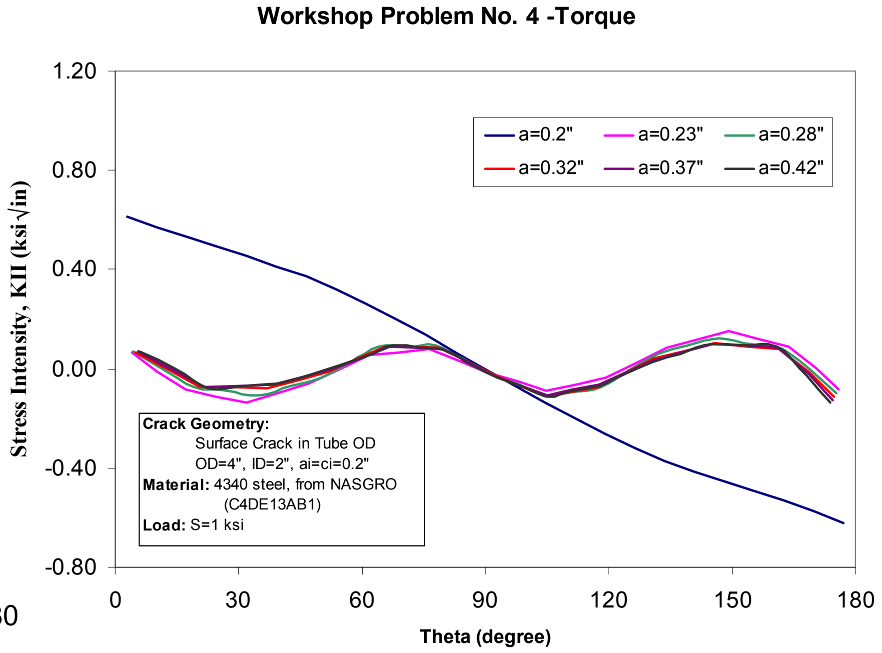
FM Code Evaluation: AGILE Workshop Problem 4 - Torsion

Comparison of BEASY and AGILE SI Solutions

BEASY Mode II



AGILE Mode II

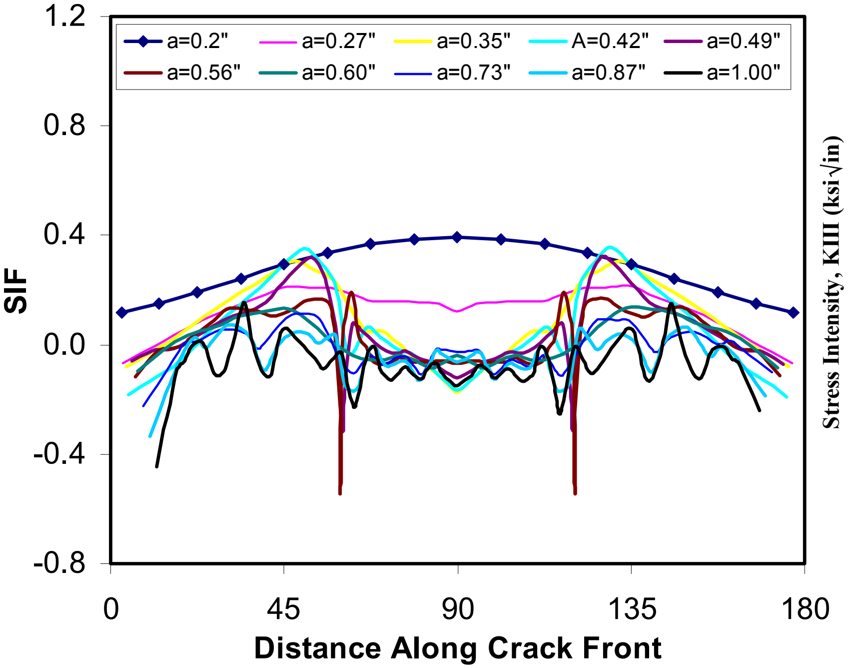


RA8: Crack Growth Analysis

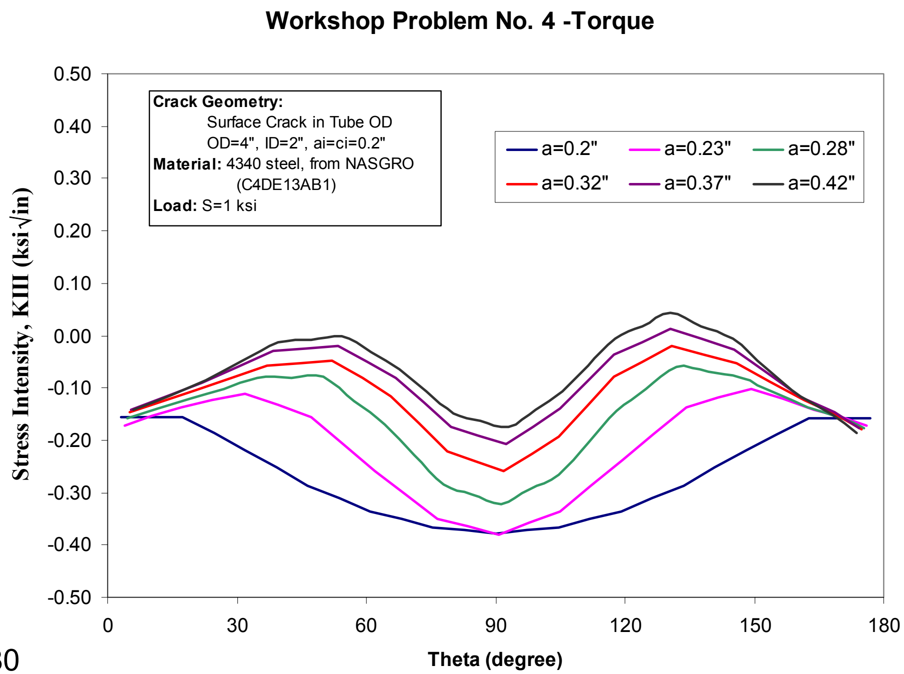
FM Code Evaluation: AGILE Workshop Problem 4 - Torsion

Comparison of BEASY and AGILE SI Solutions

BEASY Mode III



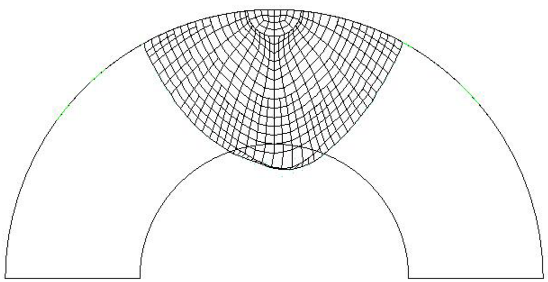
AGILE Mode III



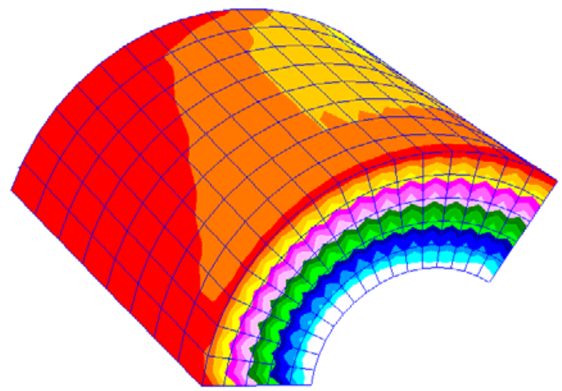
RA8: Crack Growth Analysis

Concerns Regarding BEASY

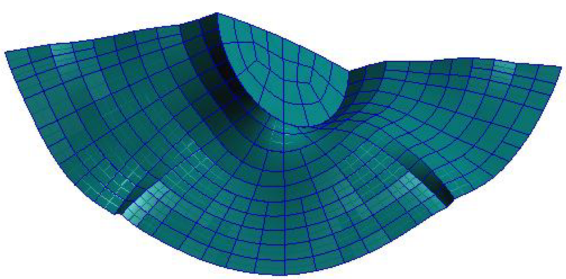
Unable to Detect Boundary



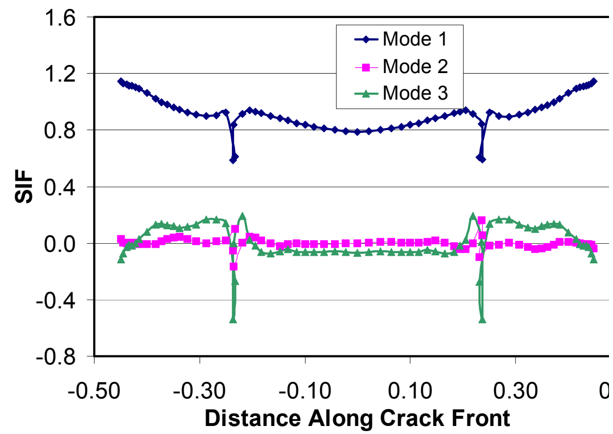
Problem with BC Transferring



Problem with Automated Growth



Problem with SI Solutions

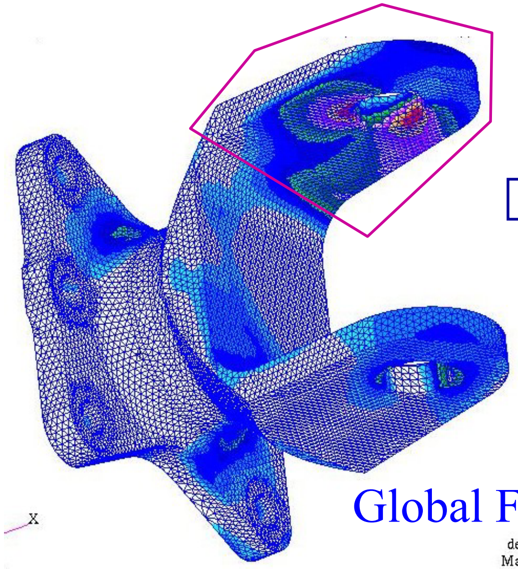


Summary of Concerns

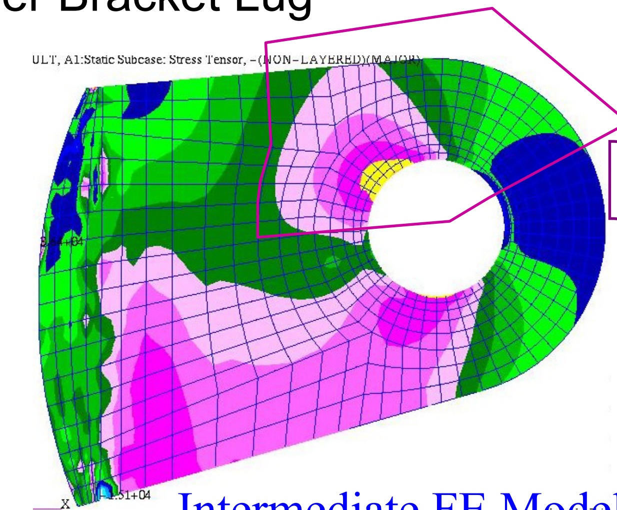
- Boundary transfer from global to local model cause stress fluctuation
- Automated crack propagation is unable to detect boundaries of the solid
- Distorted crack front and crack growth instability, lack of self convergence, crack re-mesh required
- Stress intensity spikes along crack front

RA8: Crack Growth Analysis

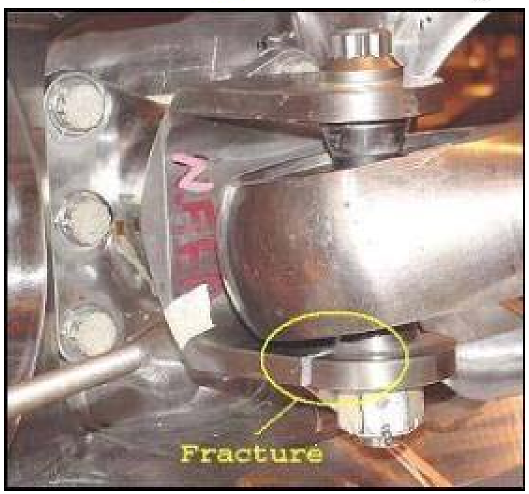
Main Rotor Damper Bracket Lug



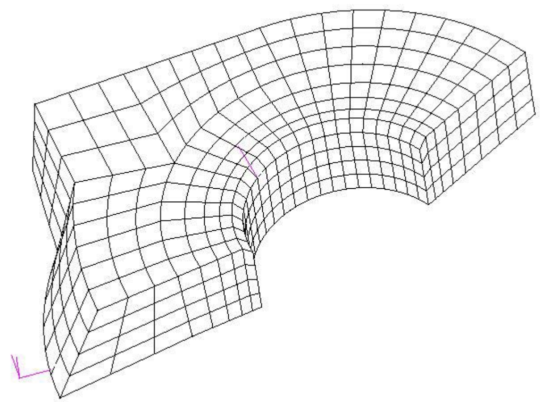
Global FE Model



Intermediate FE Model



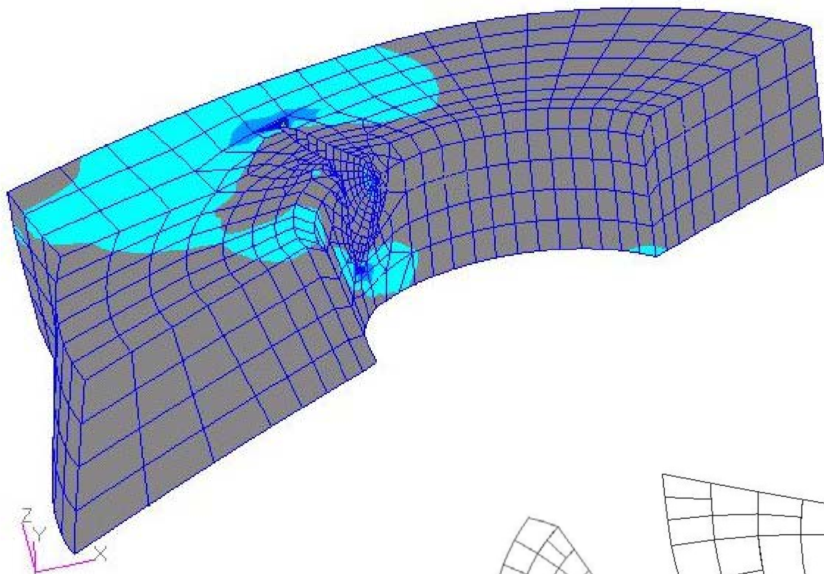
Fractured Lug After Test

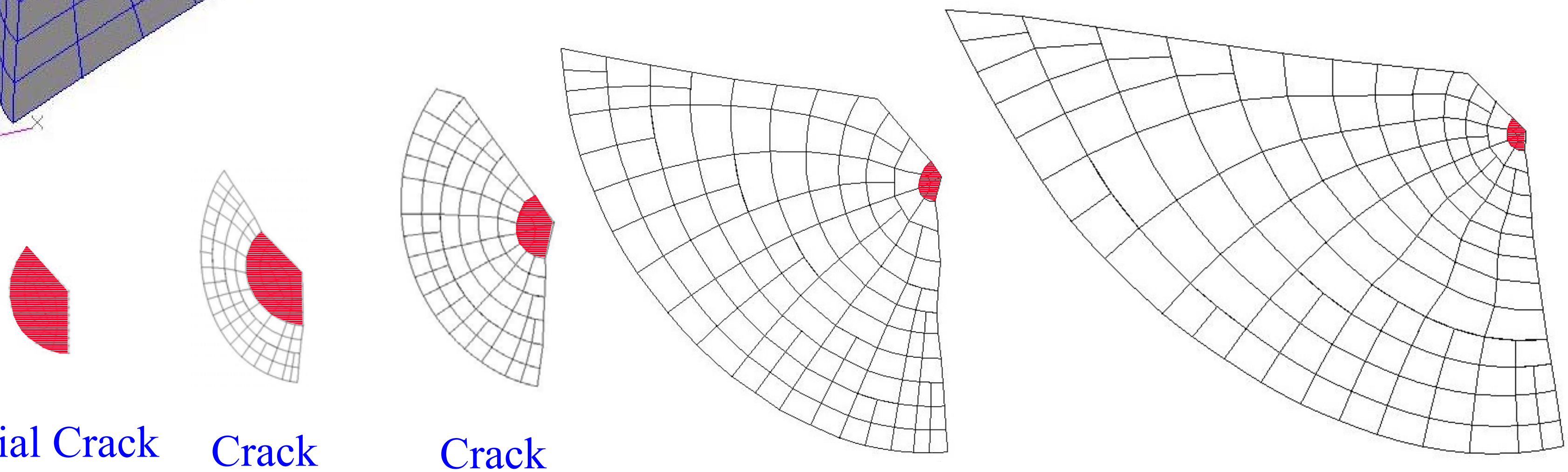


Intermediate FE Model

RA8: Crack Growth Analysis

BEASY Predicted Crack Profiles





Initial Crack Mesh

Crack Remesh 1

Crack Remesh 2

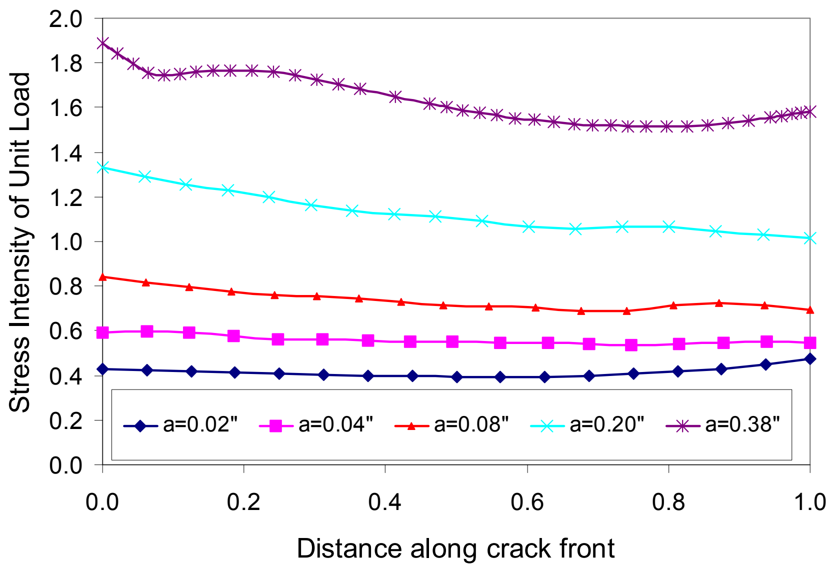
Crack Remesh 3

Crack Remesh 4

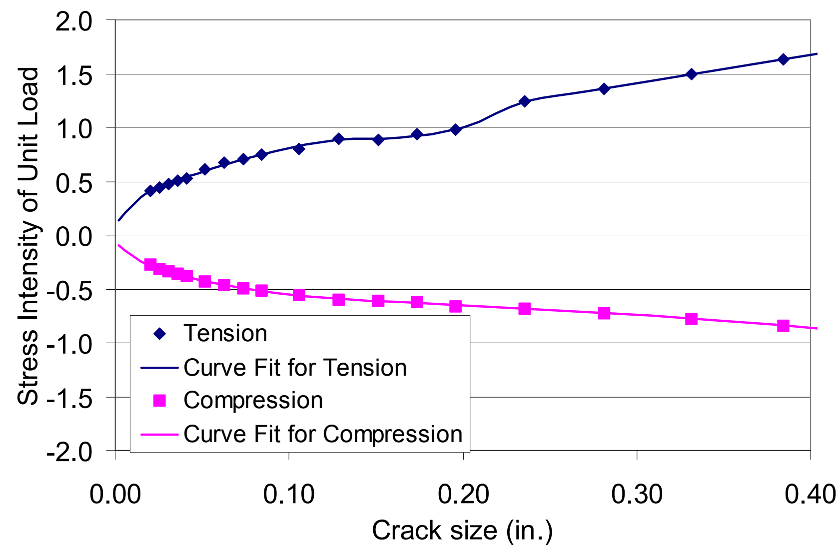
RA8: Crack Growth Analysis Methods

BEASY Stress Intensity Solutions

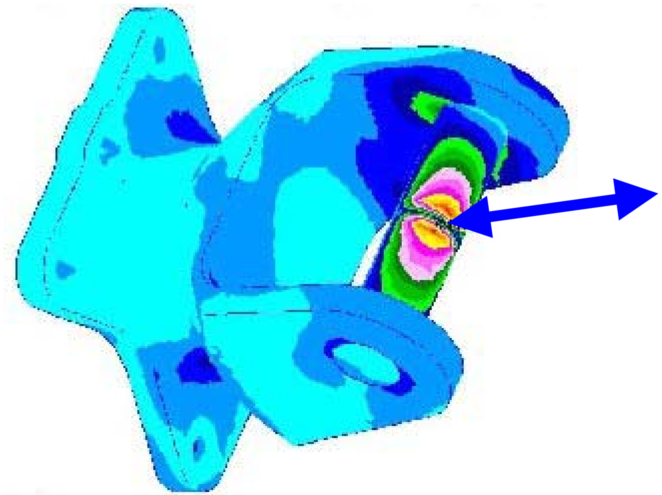
Variation SI Along Crack Front



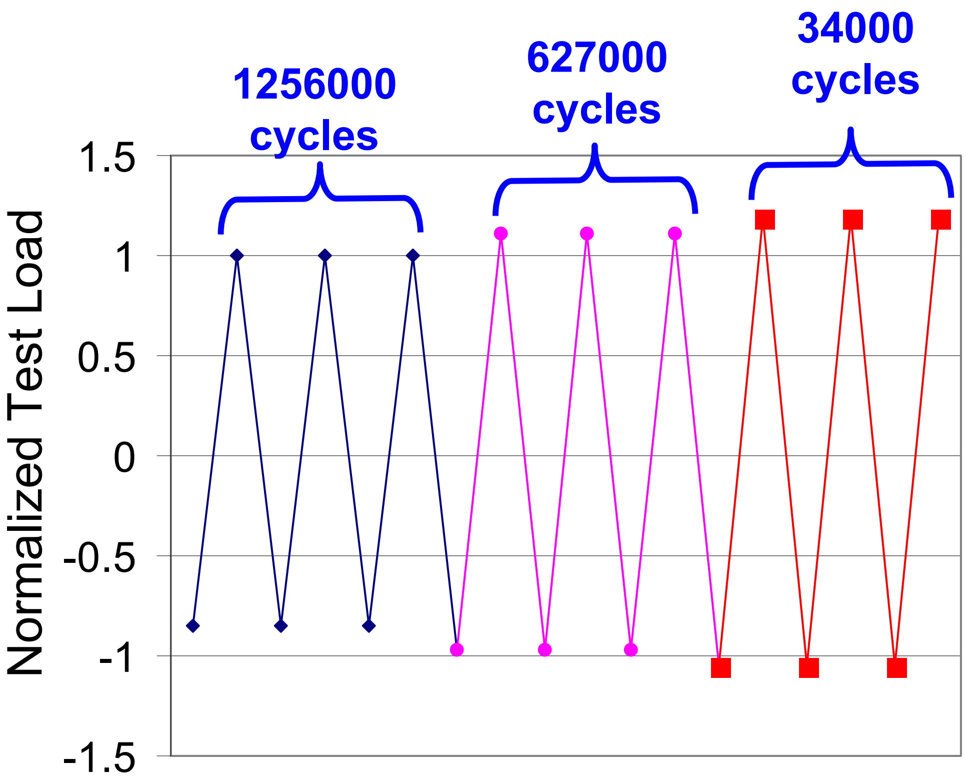
Variation SI with Crack Size



RA8: Crack Growth Analysis Methods

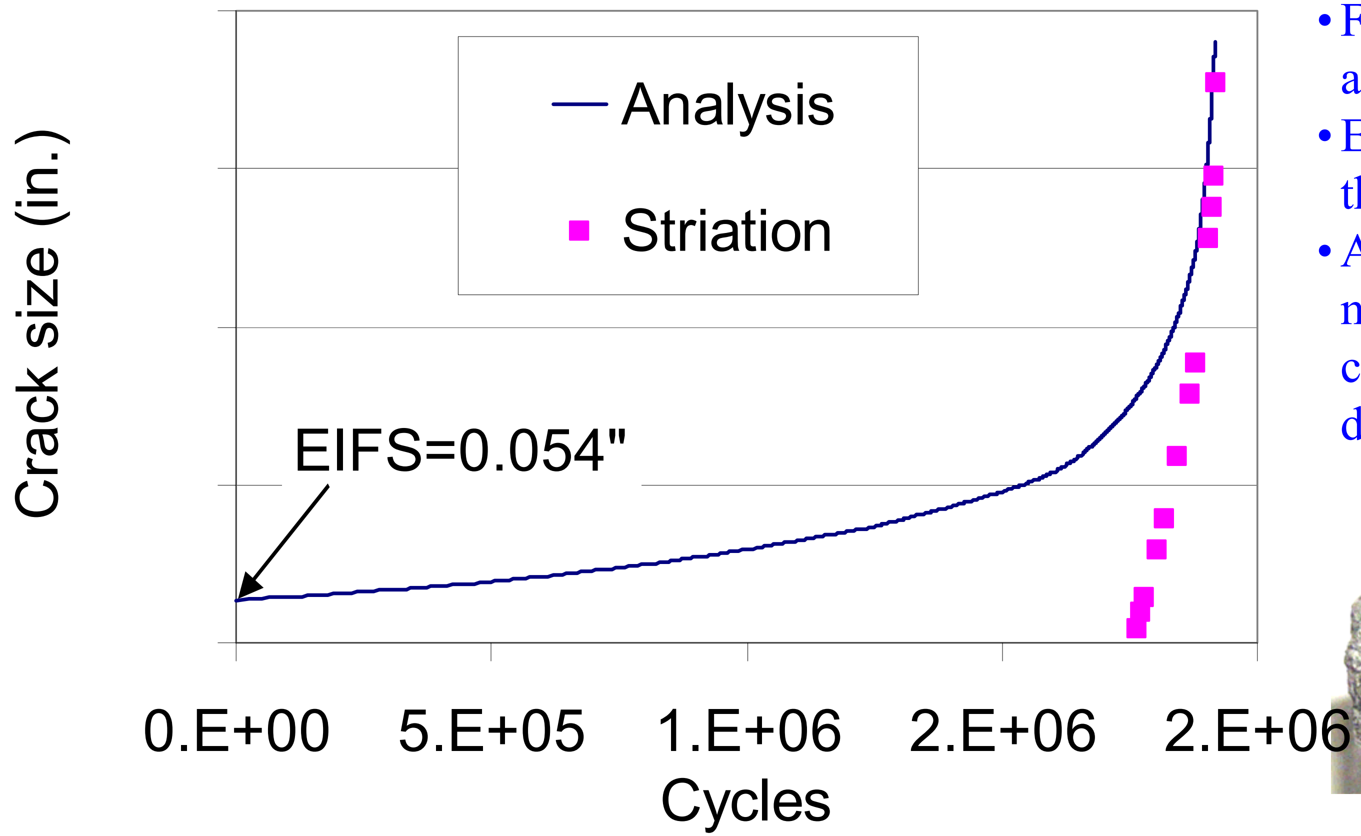


Fatigue Testing Load Spectrum

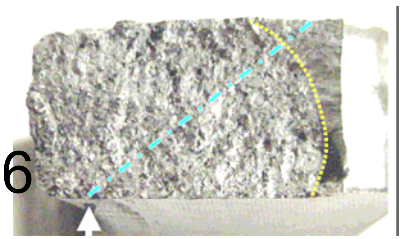


RA8: Crack Growth Analysis

Crack growth and EIFS Results

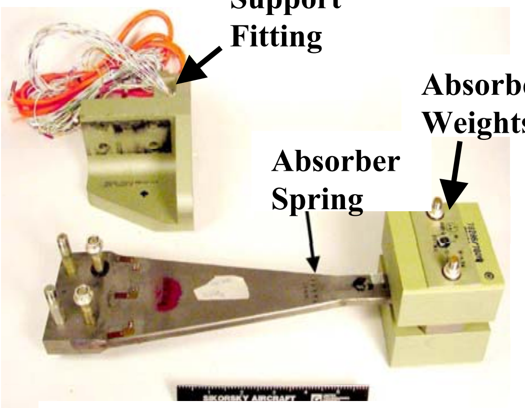


- Fretting evidenced at crack origin
- EIFS is higher than the nominal value
- Analysis-measurement correlation is poor due to fretting

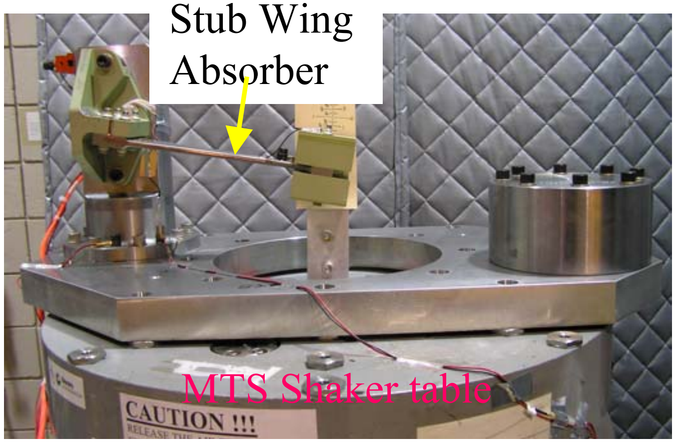


NRTC DT T&A: Test and Analysis of Laser Peening Parts

Stub Wing Vibration Absorber

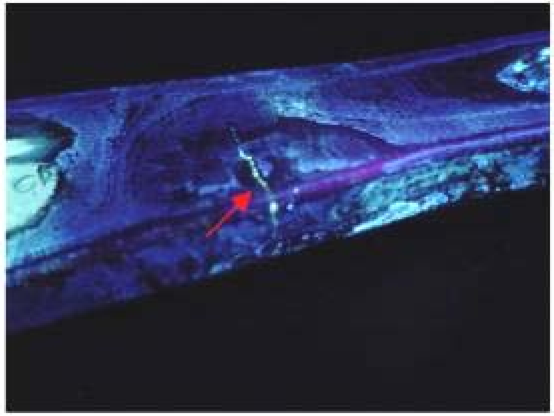


Stub Wing Absorber



Test Setup

Crack Section



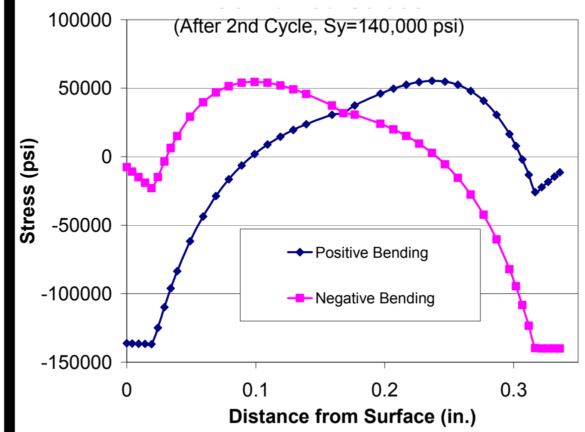
Crack Detection

- Study enhancement of laser peening to fatigue life
- Material: Ti-6Al-4V Beta STOA
- Two stub wing absorber tested, SN-1234L & SN-1235L
- Vibration fatigue testing was conducted at 25 Gs until spring was no longer able to maintain load level
- Frequency 17.3 hz

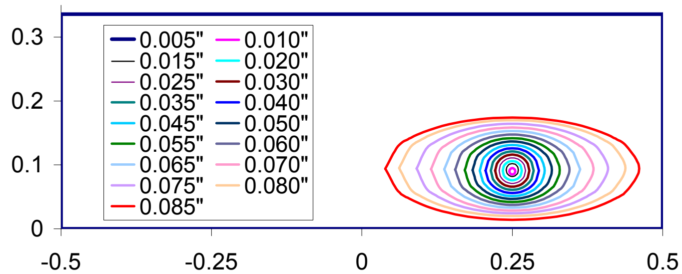
NRTC DT T&A: Test and Analysis of Laser Peening Parts

Stub Wing Vibration Absorber

Distribution of Combined Stress



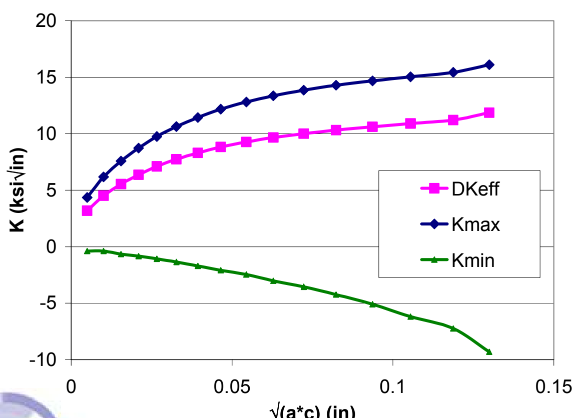
Predicted Embedded Crack Profile



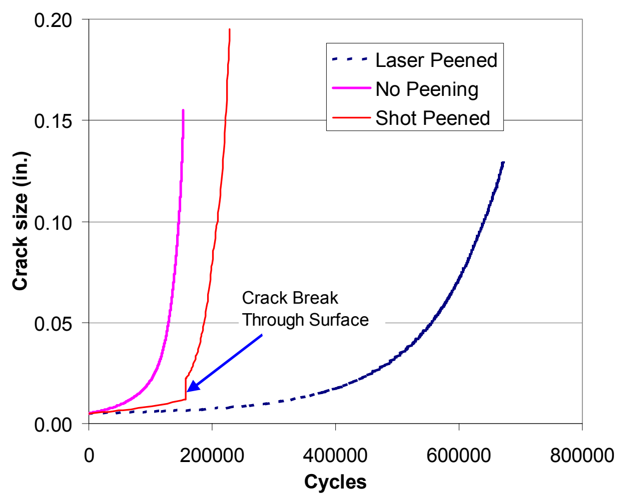
Stress Intensity Analysis

- Stress redistribution considered due to compressive yield
- Bending coursed Compressive yield at surfaces
- Crack originated at the peak effective stress
- New crack front is determined by making the effective SI along crack front be the same
- Effective stress intensity at any point is determined by the max/min SI from Newman closure model

Stress Intensity Results



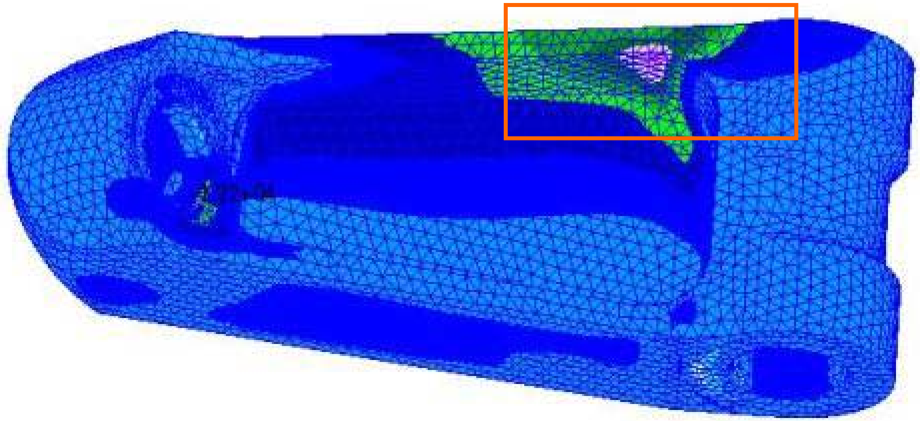
Crack Growth Analysis Results



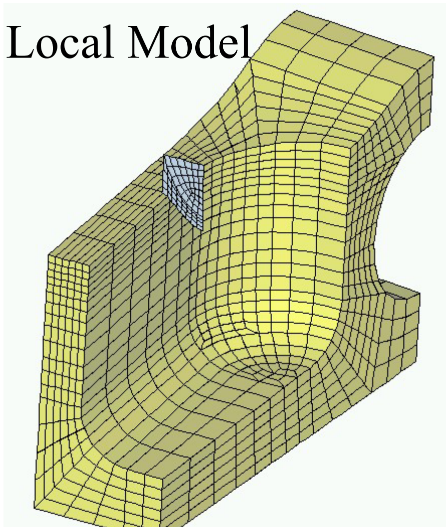
NRTC DT T&A: Test and Analysis of Full Scale Components

MR Stationary Scissors

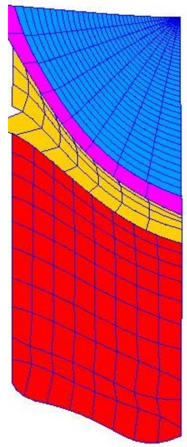
Global Model



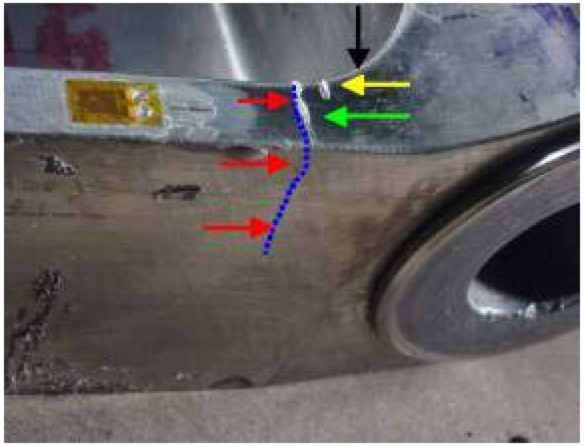
Local Model



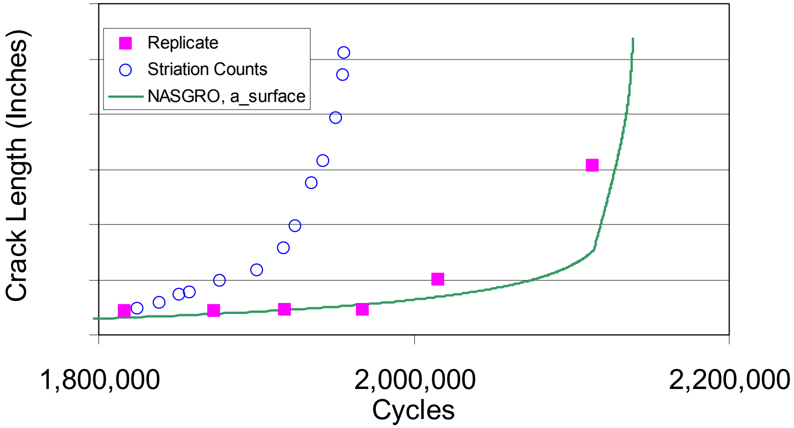
Crack Shape



Crack Testing



Analysis and Measurement Correlation



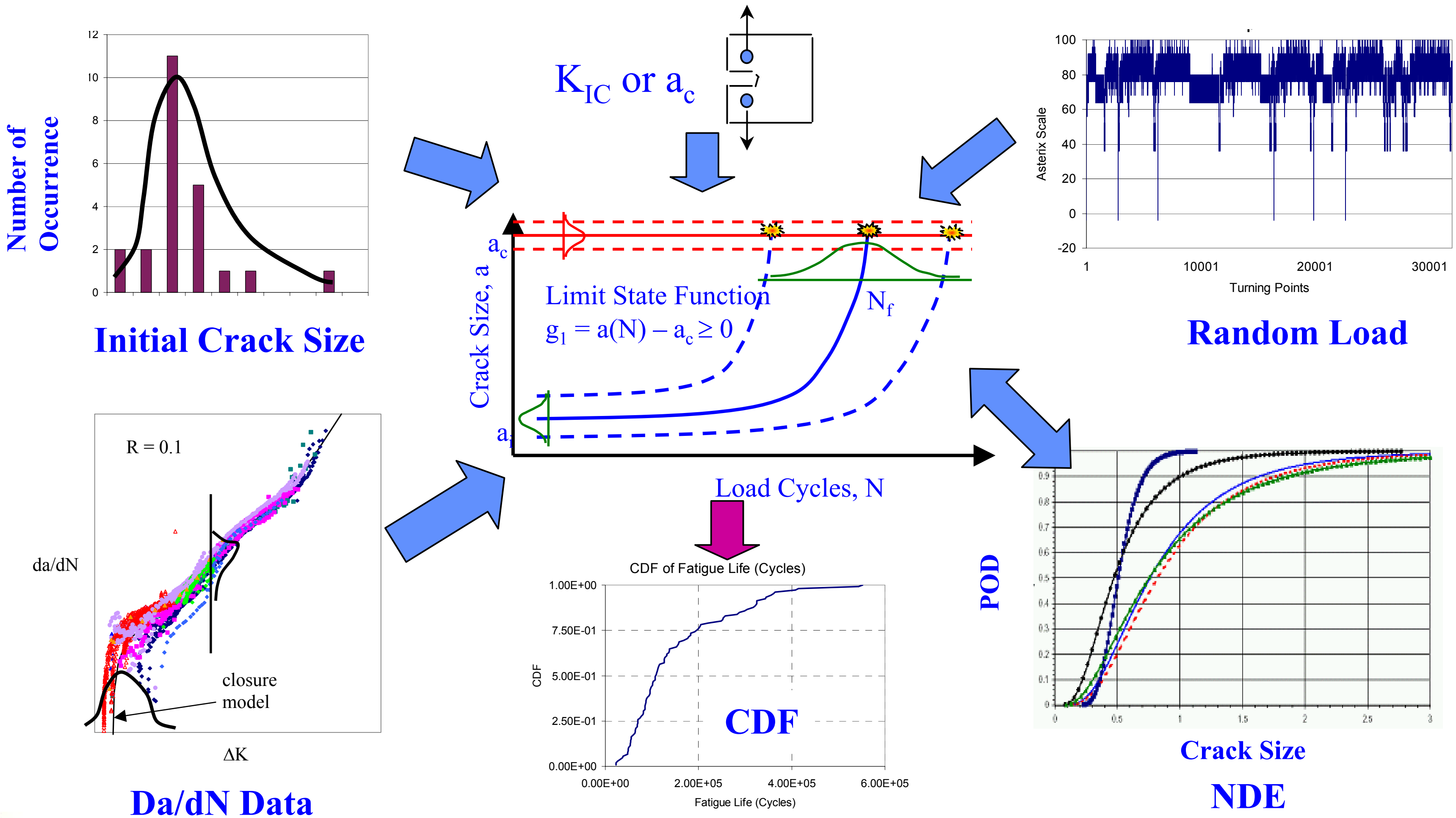
RA9: Risk Assessment

Technical Objectives

- Review risk assessment methods and tools
- Identify and characterize random variables for damage tolerance risk assessment
- Evaluate probabilistic software for determination of component life and inspection interval
- Develop probabilistic tool for crack growth analysis
- Perform damage tolerance risk analysis simulation on selected component

RA9: Risk Assessment

Probability Crack Growth Analysis Method



RA9: Risk Assessment

Review of the State-of-Art of Methods and Software

PROBAN

StruRel

COSSAN

- **Numerical Accuracy & Efficiency**
- **Robustness**
- **Technical Capabilities**
- **Customer Support**
- **Vision for Future Development**
- **Cost and Financial Stability**
- **System Interface and Integration**
- **Others**

CalRel

DARWIN

NESSUS

ProFES

ANSYS/PDS

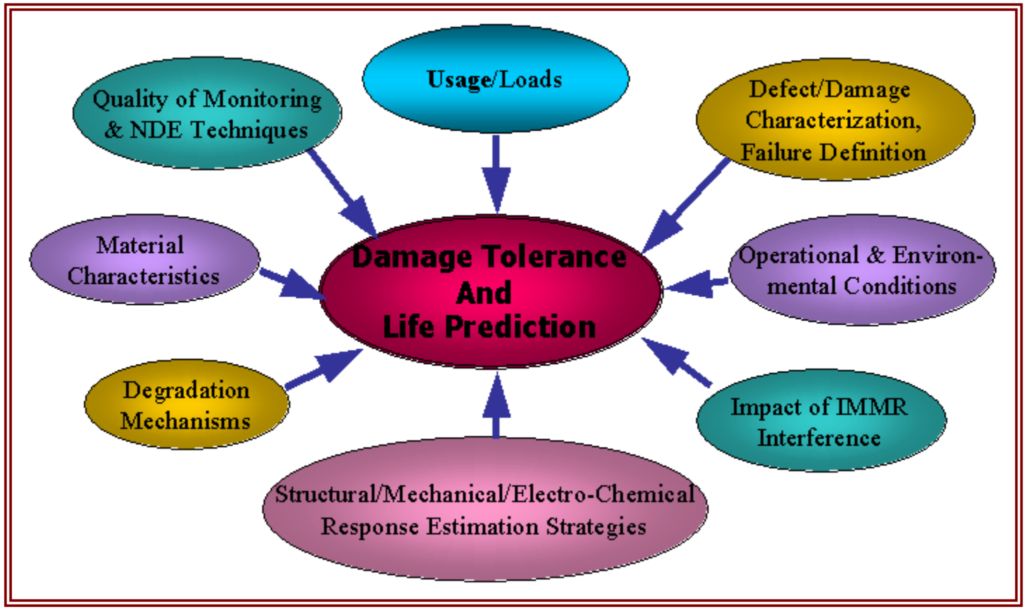
RA9: Risk Assessment

Review of the State-of-Art of Methods and Software

Major Considerations for Comparison			ANSYS	CalREL	COSSAN	NESSUS	PHMECA	PROBAN	ProFES	StruRel	UNIPASS
			Commericial Software Tools								
Front End (GUI)		Data Preprocessing									X
		Input Distribution Library	X	X	X	X	X	X	X	X	X
		Random Function/Outputs	X	X	X	X	X	X	X	X	X
		Limit State Definition	X	X	X	X	X	X	X	X	X
User Interface	FE	ANSYS			X	X			X	X	X
		NASTRAN			X	X		X	X		X
		ABAQUS						X		X	X
		Customerized							X		X
		Generic			X	X					X
Uncertainty Quantification Capability		Random Variable	X	X	X	X	X	X	X	X	X
		Random Process			X			X		X	
		Random Field	X		X			X	X		
	Correl.	Nataf Model	X	X	X	X	X	X	X	X	X
		Rosenblatt Model								X	
		Hermite Model			X			X		X	
Analysis Capability	Comp.	Probability Analysis	X	X	X	X	X	X	X	X	X
		Inverse Analysis		X				X		X	X
		CDF/PDF Analysis	X		X						X
	System	Series		X	X	X	X	X	X	X	X
		Parallel		X	X	X	X	X	X	X	X
		Compound			X			X		X	X
		Critical Failure Path ID					X				
		Time-Variant Analysis			X			X		X	
Numerical Algorithms	FORM	Gradient Based Search		X	X	X	X	X	X	X	X
		Non-Gradient Based Search									X
		SORM		X	X	X	X	X	X	X	X
		Monte Carlo Simulation	X	X	X	X	X	X	X	X	X
		Importance Sampling			X	X		X	X	X	X
		Latin Hypercub Sampling	X					X			X
Additional Features	Updating	Original Inputs									X
		Hyper-parameters						X		X	
		Outputs						X		X	
	Response Surface Method	DOX	X		X	X		X	X	X	X
		Sensitivity Check	X						X		
		Quality Check									
		Transformations									
	Sensitivity Analysis	RVs	X	X	X	X	X	X	X	X	X
		G/PoF levels		X	X	X		X	X	X	X
		Mean of RV		X				X	X		X
		Std. Dev. of RV		X				X	X		X
	Other Non-Deterministic Methods	Possibility							X		
		Fuzzy									
		Info-Gap									
		Neual Network									
		Parallel Computing	X		X					X	
		Bayesian Inference									

RA9: Risk Assessment

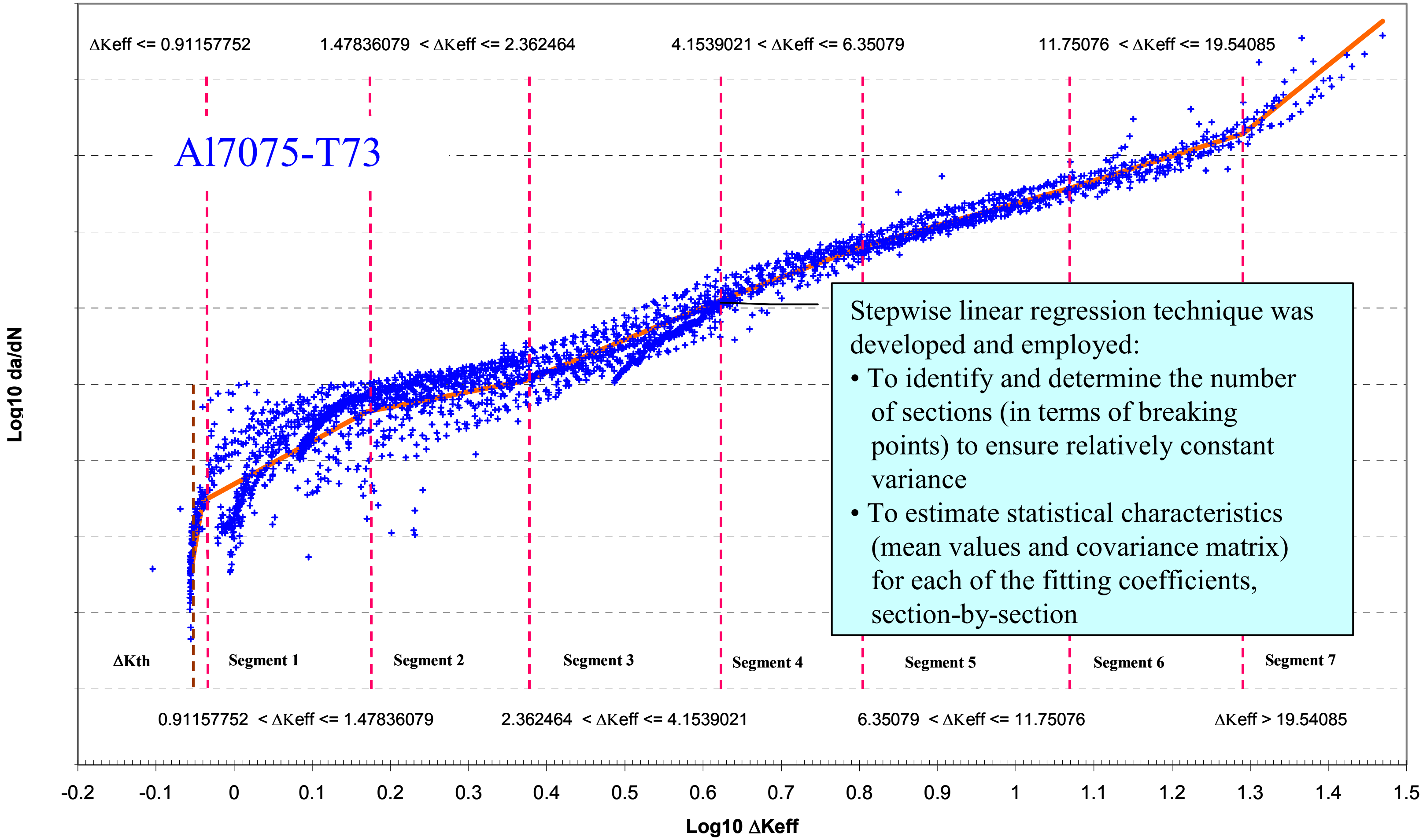
Uncertainty Identification for Damage Tolerance Risk Assessment



- **UNCERTAINTIES**
  - **ALEATORY OR CATEGORY 1 (IRREDUCIBLE)**
    - LOADS/USAGE
    - GEOMETRY
    - MATERIAL PROPERTIES
    - DEFECTS
  - **EPISTEMIC OR CATEGORY II (REDUCIBLE)**
    - MODELING ERROR
    - INSPECTION LIMITATION
    - STATISTICAL DATA BIAS
    - HUMAN ERROR

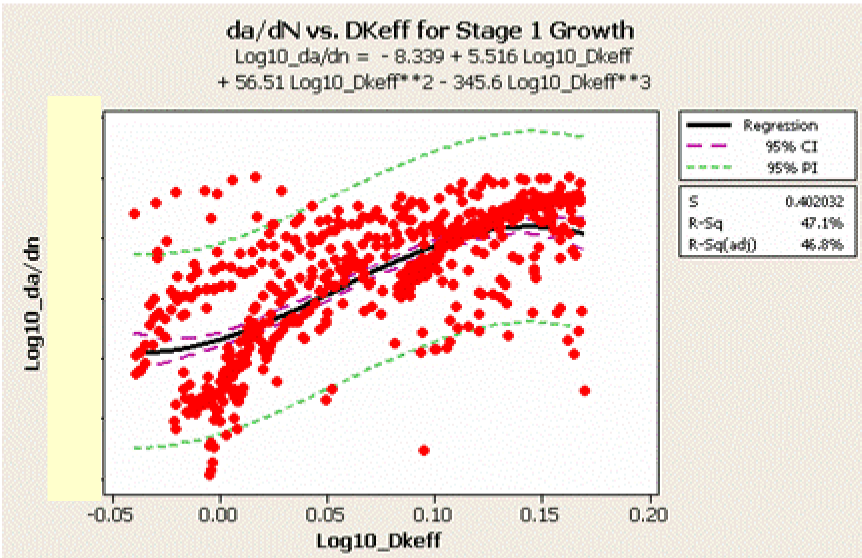
RA9: Risk Assessment

Step-wise Linear Regression Method for Statistical Representation of Crack Growth Characteristics

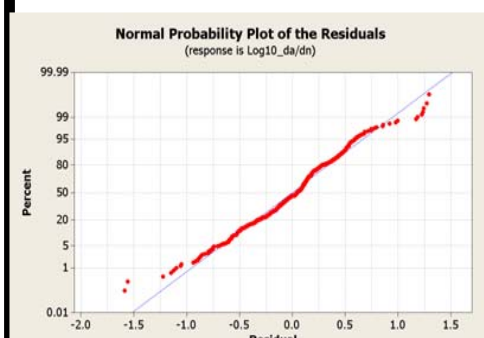


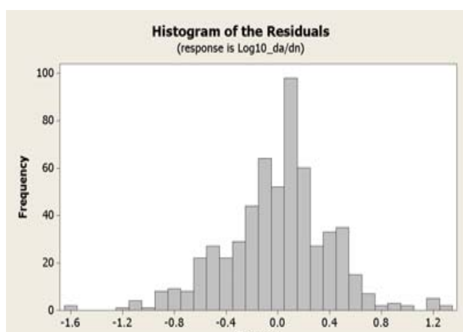
RA9: Risk Assessment

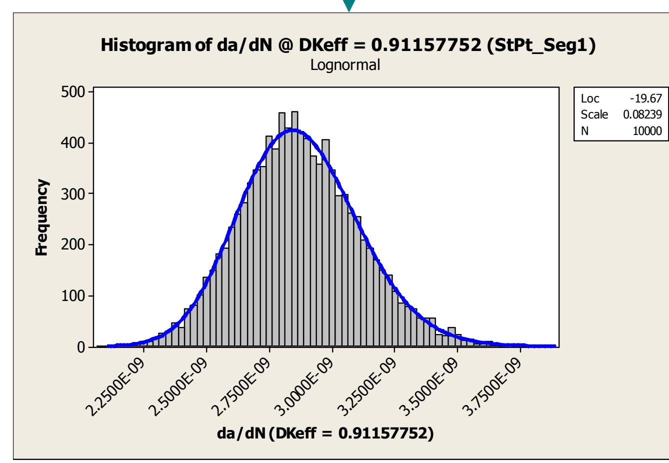
Statistical Characterizations for Crack Growth Rate @ Section 1



Statistical Characteristics for each of the regress coefficients, in terms of Mean, Std. Dev., Coefficient of Correlation and distribution type are obtained and used to quantify the scatter associated with crack growth rate at starting and ending points of each section

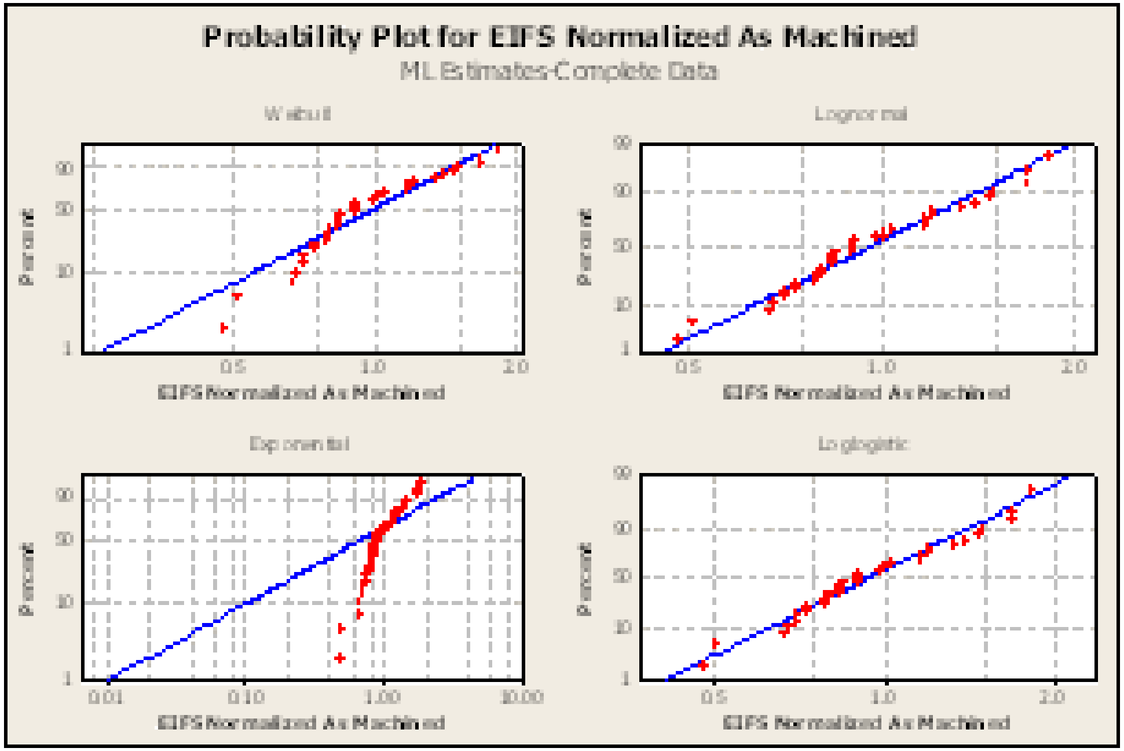


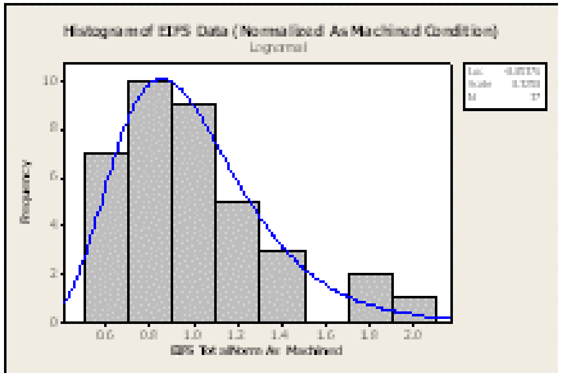




RA9: Risk Assessment

Statistical Characterizations for Initial Flaw Size





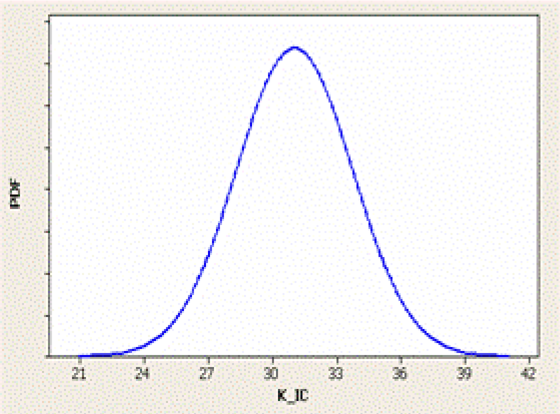
Rigorous Goodness-of-Fit Test was conducted to determine the best fitted distribution from a library of dozen distribution, including
Normal, Weibull, Lognormal, Exponential, Logistic, Loglogistic, 3P-Weibull, 3P-Lognormal, 2P-Exponential, SEV, LEV, 3P-Loglogistic

Note: EIFS for as machined condition is used as the baseline to established reference lifing for the hardware under the consideration. The statistics data used is based on coupon test results. To calibrate the statistics data obtained at component level, the mean value of the EIFS increases 3.8 times and the CoV remains the same. This adjustment is based on limited component test data at as-machined condition.

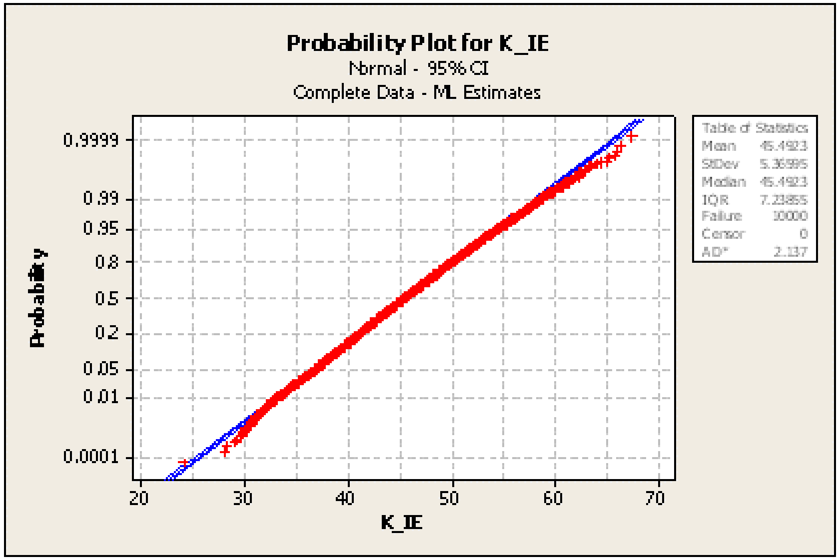
RA9: Risk Assessment

Statistical Characterizations for Fracture Toughness

			Max	Mean	Min	CoV	Std. Dev
7075-T73 (K_{IC})	Die Forging	T-L	25	21	18	0.099	2.079
	Hand Forging	***L-T***	***39***	***31***	***29***	***0.088***	***2.728***
	Hand Forging	T-L	27	23	20	0.09	2.07



$$K_{IE} = K_{IC} \times \left(1 + C_K \times \frac{K_{IC}}{\sigma_{YS}}\right)$$

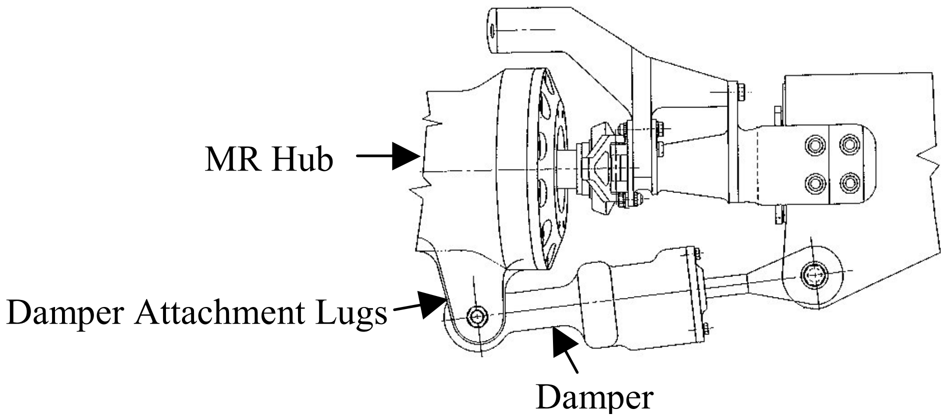


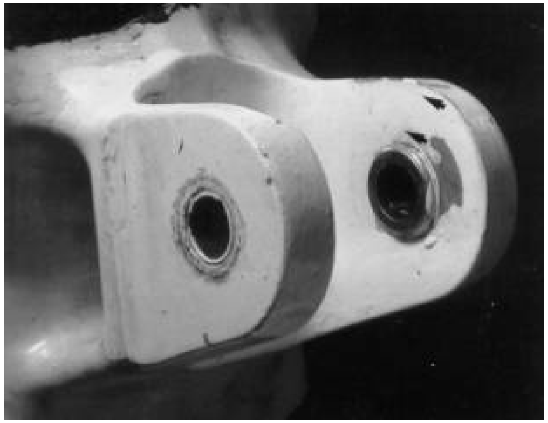
Statistical Model for K_{IE} is obtained through numerical simulation using NASGRO equation and statistical data for K_{IC} as reported in Mil-HDBK 5J

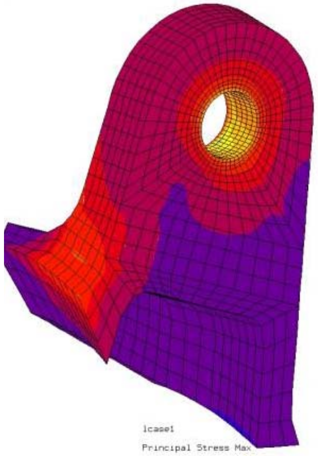
7075-T73 (K_{IE})			Mean	Std. Dev	Dist Type
	Hand Forging	***L-T***	45.49	5.366	Normal

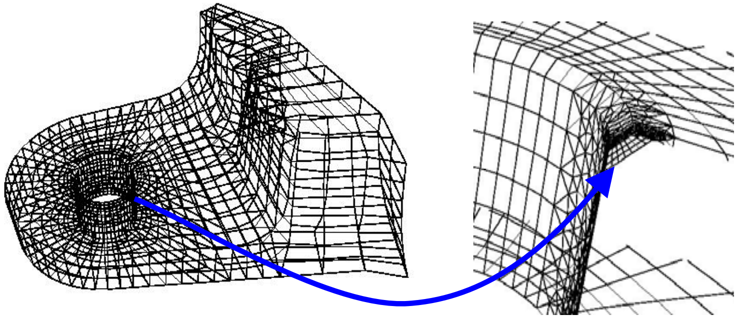
RA9: Risk Assessment

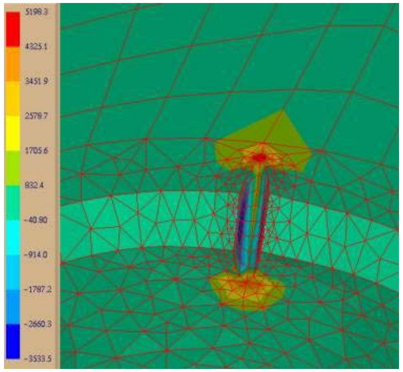
Probabilistic Crack Growth Damage Tolerance Demonstration
MR Damper Lug





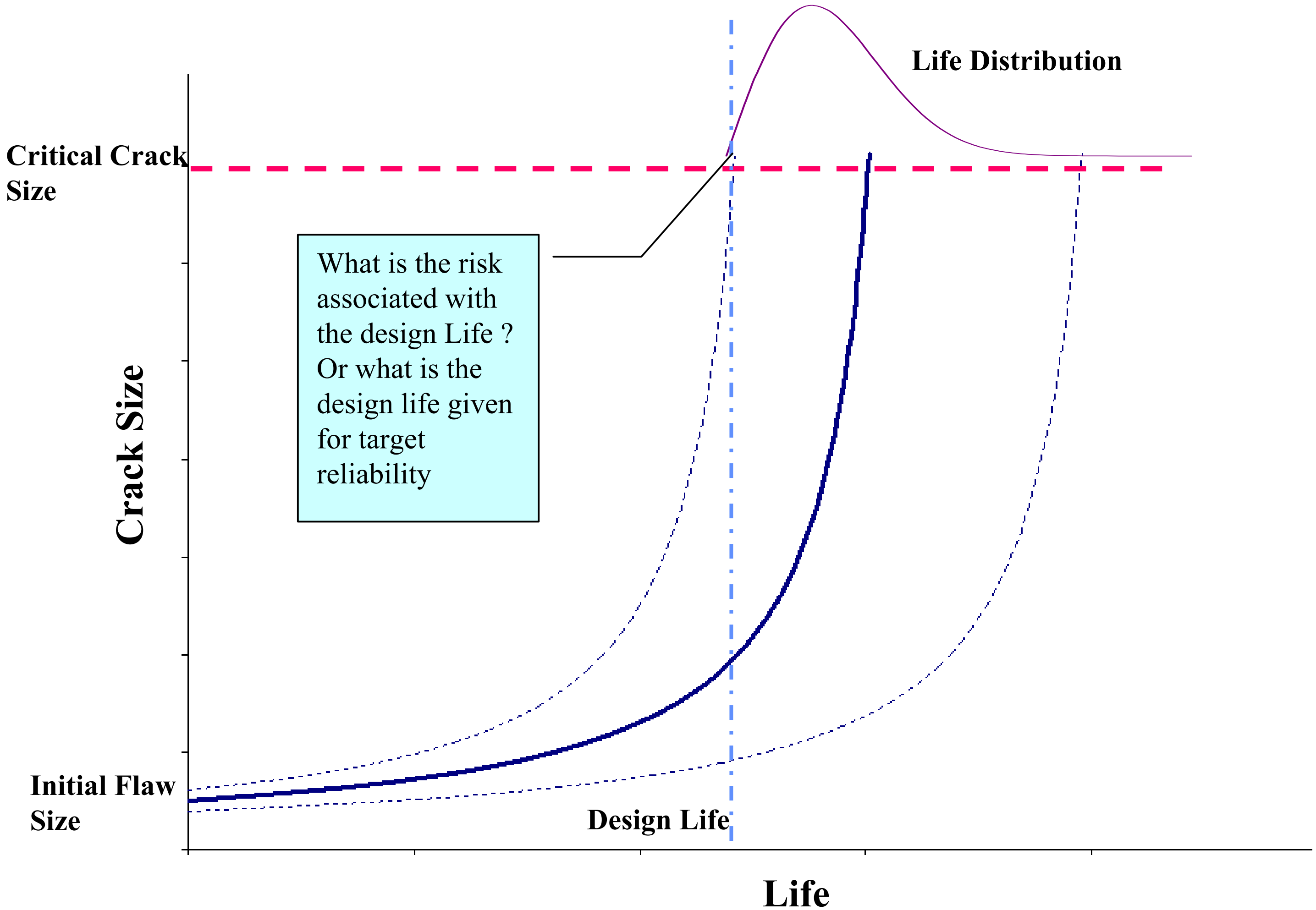






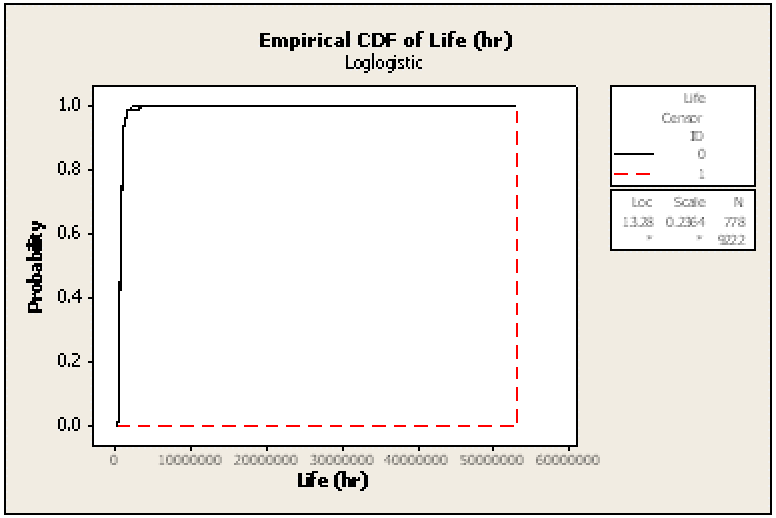
RA9: Risk Assessment

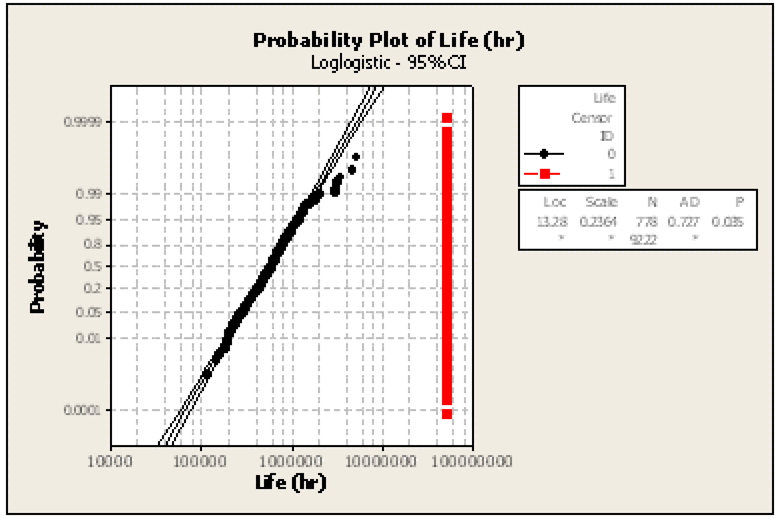
Probabilistic Crack Growth Life Prediction and Inspection



RA9: Risk Assessment

Probabilistic Crack Growth Life Prediction for MR Damper Lug



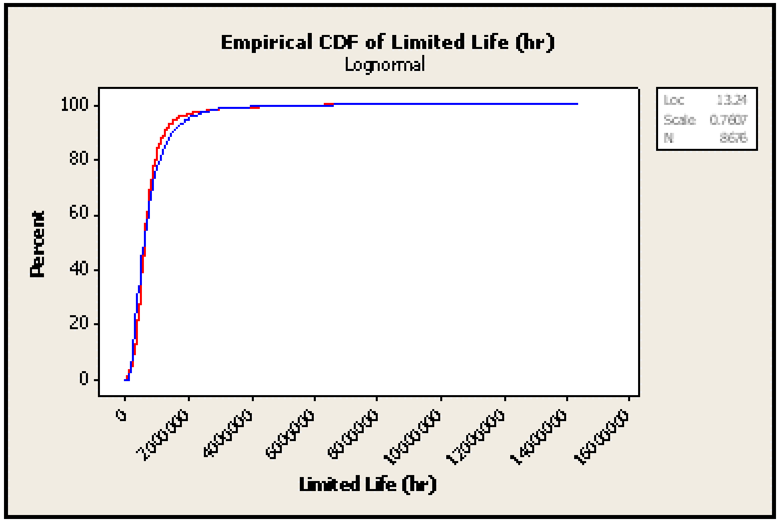


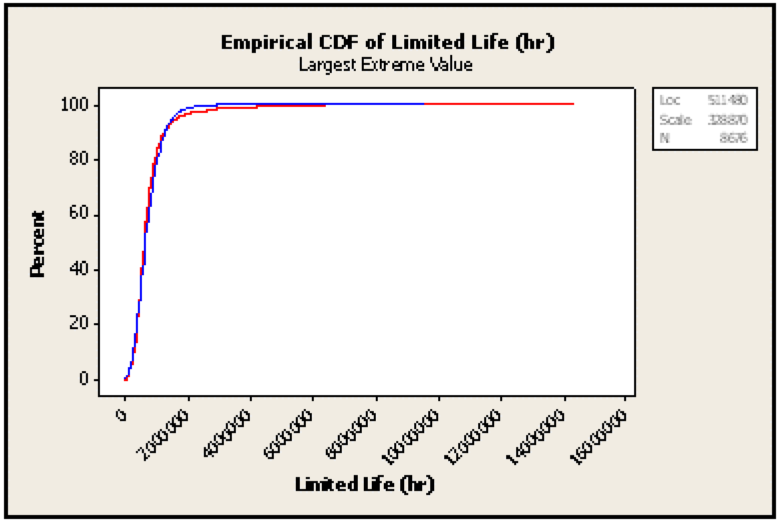
In Nasgro analysis, sometimes, the output for life to failure will not be calculated, if the effective stress intensity range at given crack size is smaller than the stress intensity threshold. In the probabilistic Nasgro analysis for this case study, majority of samples have "infinite life". As shown in the plots above, the statistical characterization for both populations (limited life data and "infinite life" data) are performed.

- The estimated life to failure at three load scatter levels considered (CoV = 5%, 10%, and 15%) exceeds the design target with risk of failure significantly below the requirement for meeting Six 9 Reliability.
- It is observed that increase of uncertainty associated with load (via load scale factor) significantly decreases the estimated life to failure at given risk levels.

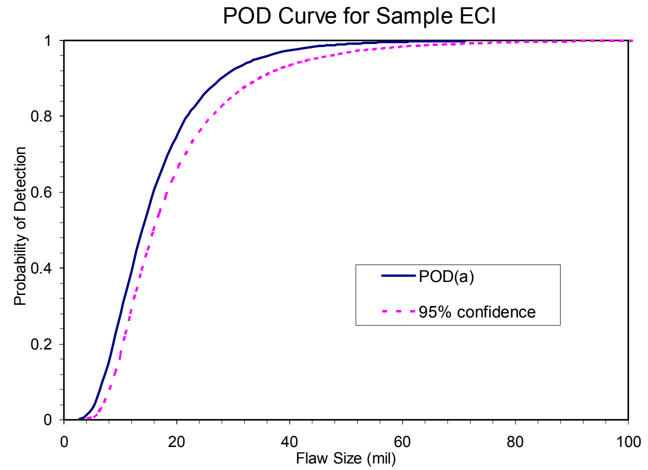
RA9: Risk Assessment

Probabilistic Inspection Interval Prediction for MR Damper Lug





<u>Results are based on ECI POD</u>



- The estimated inspection interval satisfying the Six 9 Reliability requirement is calculated
- Uncertainty associated with load (via load scale factor) significantly affect the inspection planning. It is highly desirable to reduce the scatter associated usage and loadings through HUMS to achieve optimal inspection planning.

RA9: Risk Assessment

Summary of Accomplishment

- Conducted comprehensive technical review for probabilistic methodology and software packages for uncertainty propagation and reliability/risk analysis.
- Developed a preliminary flow-map for uncertainty Identification process pertinent to damage tolerance risk assessment applications.
- Developed a stepwise regression analysis approach and performed rigorous statistical analysis for Al 7075-T73 crack growth data and conducted comprehensive statistical analysis and distribution fitting for crack growth characteristics and EIFS with a library of a dozen statistical distributions.
- Developed probabilistic crack growth damage tolerance models and analysis procedure by integrating fracture mechanics based crack growth tool with probabilistic analysis engine for determination of component life and inspection interval based on reliability level and uncertainties of selected variables
- Enhanced interface framework between ProFES and NASGRO and streamlined the logics of interface for future extension for "Generic Interface"
- Demonstrated the concepts and framework of probabilistic fracture mechanics analysis through case study for a MR Damper Lug

Technical Accomplishments In 2005

RA 4: Crack Growth Data

Coordinated with NASA and MSU on developing material CG data and testing methods. Supplied specimen blanks and material properties to MSU

RA 6: Certification Testing

- Completed two full-scale component fatigue testing and striation counts.
- Fatigue tested 27 as-machined and flawed coupons with open hole

RA 8: Crack Growth Analysis

- Completed BEASY stress intensity and crack growth analysis, striation count and analysis/measurement correlation for the S-92 MR damper lug.
- Performed crack growth and EIFS analysis for flawed coupons
- Performed BEASY stress intensity for an AGILE workshop problem. Completed a BEASY model for a landing gear cylinder

RA 9: Risk Assessment

- Identified random variables and determined PDFs for these variables.
- Developed probabilistic crack growth model and procedure.
- Demonstrated the probabilistic DT method through a case study.

Report: Submitted a draft version of FAA RCDT Specific Issue report.

Recommendations And Planned Research

- Material defect, manufacturing quality and in-service damage characterization
- Loading interaction model for helicopter high/low cycle loading spectrum
- Fracture mechanics analysis methods and code improvements for DT assessment of complex rotorcraft dynamic components, including 3D non-planner crack growth
- Probabilistic damage tolerance analysis approaches, codes, and data
- Material crack growth and threshold data and testing method development
- Development of analysis methods for life-enhancement techniques, including laser peening, cold working, and cold expanded busings.